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16. ABSTRACT

The utilization of porous pavement in parking lots and other applications where stormwater detention is required provides a control strategy capable of mitigating the detrimental aspects of urban runoff. A study of porous and conventional pavement systems in Austin, Texas was undertaken, the objectives of which were: 1) review of past experience with porous pavements, 2) development of a mix design and construction specifications for a porous asphalt concrete system and construction of a porous asphalt parking lot, 3) performance evaluation of porous and non-porous pavements, and 4) development of a design methodology for porous pavement stormwater storage systems. The report includes details of pre-construction planning, construction and post-construction testing. Each study pavement was instrumented for climatic, hydraulic and water quality sampling. Observed pavement discharge hydrographs were compared with those simulated using a revised version of PORPAV, a computer program which models the stormwater hydraulics of a porous pavement facility. The model calibration and verification results provide an insight into the capabilities of PORPAV and its potential application to future studies where similar porous pavement projects are desired. The hydraulic relationships incorporated in PORPAV were utilized in the development of a methodology to aid engineers and developers in the design of porous pavement systems.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and for minimizing the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report provides design, construction, and performance data for porous pavements used for parking lots and other applications where stormwater management is required to mitigate the detrimental aspects of urban runoff.

Francis T. Mayo, Director
Municipal Environmental
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ABSTRACT

Physical alterations of a watershed associated with urban development have been recognized as a source of stormwater hydrologic and water quality impacts to indigenous water resources. The utilization of porous pavement in parking lots and other applications where stormwater detention is required provides a control strategy capable of mitigating the detrimental aspects of urban runoff. This report addresses the stormwater hydraulic and quality characteristics for several porous and conventional nonporous pavement systems during and subsequent to natural and simulated storm events.

A study of porous and conventional pavement systems in Austin, Texas was undertaken, the objectives of which were: 1) review of past experience with porous pavements, 2) development of a mix design and construction specifications for a porous asphalt concrete system, 3) performance evaluation of porous pavements, and 4) development of a design methodology for porous pavement stormwater storage systems. This report includes details of preconstruction planning, placement of the porous asphalt surface course, the results of indirect tensile strength testing, in situ porosity results, and the results of a visual inspection after 18 months of vehicle use.

Each pavement evaluated was instrumented for climatic, hydraulic and water quality sampling. Observed pavement discharge hydrographs were compared with those simulated using a revised version of PORPAV, a computer program which models the stormwater hydraulics of a porous pavement facility. The model calibration and verification results provide an insight into the capabilities of PORPAV and its potential application to future studies where similar porous pavement projects are desired.

The hydraulic relationships incorporated in PORPAV were utilized in the development of a methodology to aid engineers and developers in the design of porous pavement systems. The design methodology presented herein incorporates the hydraulic relationships of rainfall intensity, pavement and base permeability and soil infiltration rates among others, into a general procedure for the design of porous pavement lots. The versatility of the methodology allows its application to various design objectives, including:

- a wide range of site and design storm characteristics;
- sizing the pavement facility for volume or discharge limitations;
- the option of using an impermeable boundary to prevent leakage; and,
- the option of utilizing a collection drain within the porous base.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Cross-sectional area of flow
A_c	Area of contributing watershed
A_p	Area of porous pavement system
C	Degrees centigrade
cfs	Cubic feet per second
cm/hr	Centimeters per hour
cm	Centimeter
D	Thickness of the porous pavement base layer
d_b	Depth of water in the porous pavement base layer
d_s	Depth of water on the pavement surface
F	Degrees Fahrenheit
ft^3	Cubic feet
H	Total elevation potential
hr	Hour
i	Average inflow to the porous pavement system
i_f	Infiltration capacity of the soil
i_o	Initial soil infiltration rate
i_r	Average rainfall on the pavement during the runoff duration
i_s	Soil infiltration rate
in	Inch
in/hr	Inches per hour
k	First-order infiltration rate decay coefficient
K_b	Permeability of the base media
K_f	Permeability of the filter course or cloth
kg	Kilogram
K_p	Permeability of the pavement surface
l	Liter
L	Length of porous pavement system, parallel to slope

LIST OF ABBREVIATIONS AND SYMBOLS (Concluded)

L_n	Horizontal distance between each pipe in a multiple pipe system
l/s	Liters per second
m	Meter
m^3	Cubic meters
n	Manning's coefficient of roughness
N	Number of lateral collection drains
n_b	Porosity of base media
pcf	Pounds per cubic foot
psi	Pounds per square inch
Q	Volumetric flow rate
Q_b	Discharge from porous pavement base
q_b	Discharge from the porous pavement base per unit area
Q_c	Surface runoff from contributing area
q_p	Discharge capacity of drain pipe per unit area of the porous pavement system
Q_s	Surface runoff from porous pavement area
q_s	Surface runoff from porous pavement per unit area
S	Slope of the energy grade line
S_b	Slope of the base layer
t	Elapsed time
t_c	Time of concentration for contributing area
t_d	Duration required to drain porous pavement storage capacity
t_f	Duration required to fill porous pavement storage capacity
t_r	Design storm runoff duration
V	Total volume of discharge from the porous pavement system
w	Width of porous pavement system

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Mr. John German, City of Austin, Assistant City Manager and former Director of Public Works, and his predecessor at the City of Austin, Mr. Charles Graves, whose interest, commitment, and early recognition of the potential benefits of developing a set of guidelines for the design and construction of porous pavement, were instrumental in the initiation of this grant. The efforts of Mr. Jim Berry and Mr. Ramon Miguez, and his predecessor, Mr. Troy Ulmann, of the City's Watershed Management Division were essential to the preparation and construction of the study parking lots and the instrumentation for and monitoring of storm and simulated storm runoff. Mr. Chris Chambers, also with the City's Watershed Management Division, participated in the data collection of simulated runoff events.

At Espey, Huston & Associates, Inc., Mr. Elvidio Diniz was responsible for the design and execution of the study. In 1982, Mr. Gary Guhl succeeded him as Project Manager. Mr. Ron Boyd supervised the field work and preliminary data processing. Mr. Keith Leerssen directed the fabrication and installation of the stormwater monitoring equipment and was essential to day-to-day operation and maintenance of the monitoring equipment.

Dr. Brent Rauhut of Brent Rauhut Engineering, Inc. was involved in the specification, design, and construction of the porous asphalt lot in the Austin project. Dr. Rauhut with Mr. Phil Clark, Trinity Engineering Testing Corporation and Mr. Homer Henry of Capital Aggregates provided input during the construction of the porous asphalt lot. Dr. Rauhut authored Section 5 of the report, Pavement Construction.

Mr. James Arnst, Water Quality Services Supervisor, Mr. Mike Peters, Regional Laboratory Director and Ms. Debbie Magin of the Guadalupe-Blanco River Authority supervised all analytical laboratory efforts.

SECTION 1

INTRODUCTION

This project was undertaken at the initiative of the U.S. Environmental Protection Agency (EPA) and the City of Austin, Texas. The City is very active in basin-wide urban drainage management and non-point source pollution control and has established watershed ordinances as a direct result of environmental awareness by the general public and responsive local legislation. The results of this project could enhance the City's ability to protect its valuable water resources.

BACKGROUND

The liabilities of urban development to indigenous water resources are generally accepted to be manifested in stormwater runoff peaks and event volumes of greater magnitude than in the predeveloped state, often occurring in association with a degradation of receiving water quality. The development of impervious areas such as roofs, streets, and parking lots in urban areas reduces the infiltration capacity of urban watersheds and produces a corresponding increase in runoff rates and volumes. Stormwater runoff from developed areas has been recognized as a source of contaminant loading to surface and ground water resources. Stormwater flows transport contaminants which accumulate on the watershed during dry weather, however, the total mass transported is a function of the contaminant accumulation rate, the number of preceding dry days, the intensity of the rainfall, the velocity and volume of surface flow and other physical properties of the catchment. Impervious areas generally have limited assimilative properties and in some cases tend to yield contaminants that are not amenable to control and removal using standard maintenance procedures. Heavy metals, oils and other hydrocarbons from automobiles and machinery, suspended solids from dust and dirt accumulation and airborne pollutants washed out during precipitation events are typical contaminants present in urban stormwater runoff.

Efficient and effective urban drainage design is predicated on an accurate evaluation and understanding of the hydrologic and water quality changes associated with land development. Often there is the need to satisfy watershed drainage and pollution control criteria which do not allow an increase in runoff rates or contaminant loads above predevelopment conditions. Stormwater management generally consists of collecting and transporting overland runoff in a conveyance system of storm sewers and possibly channels which are tributary to a nearby stream or lake. Although local flooding problems may be solved by this method, the shorter time of concentration and higher peak flows which are generated may create more severe flood problems downstream. The increase in flow velocities in the improved channels creates a high erosion and scour potential, thus exacerbating the problem of pollutant transport to receiving bodies of water.

GENERAL CONTROL PRACTICES

A typical urban development scenario involves a contributing watershed with a large percentage of impervious cover, such as a shopping center with buildings and associated parking areas. As a measure to protect the water quality of receiving waters, some municipalities have implemented ordinances which require construction and maintenance of stormwater control facilities which mitigate adverse water quality impacts. Stormwater runoff is routed either overland or through storm drains to a detention facility. These ordinances typically require detention facilities be designed to capture, and subsequently detain for a specified time, the initial volume of stormwater runoff, reflecting the general concern of removing the first-flush of constituents. An effective removal mechanism for suspended constituents is settling, taking advantage of the relatively quiescent conditions provided by the detention facility. Periodic maintenance may be necessary to remove accumulated sediment to avoid resuspension during scouring from subsequent influent. Another commmon treatment is filtration through sand or other media. To prevent clogging, the filter beds need to be scraped periodically. After a designated detention period (commonly 24 hours), the stormwater volume is discharged into receiving waters, or, in older cities, to a sanitary sewer collection system to receive further treatment.

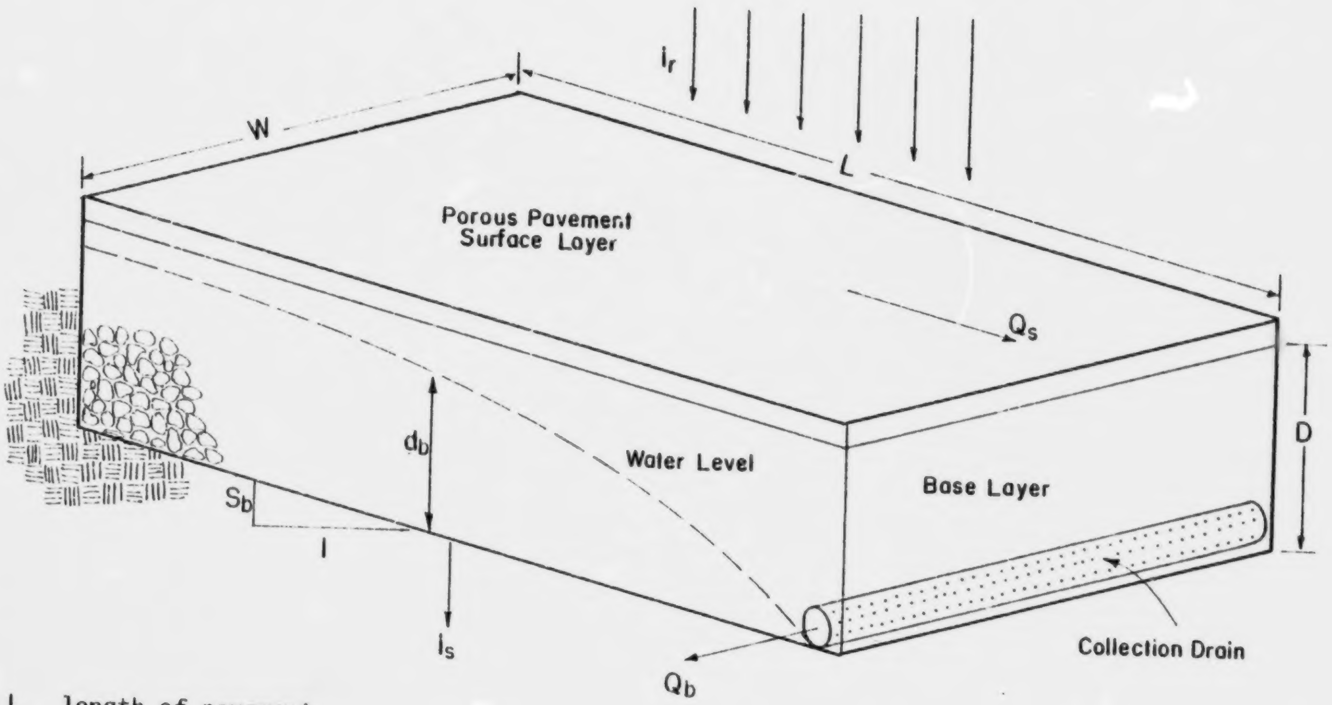
Other stormwater management options include:

a. maintenance of natural drainage patterns and limiting the amount of impervious cover to prevent excessive erosion and to allow deposition of suspended stormwater constituents;
b. runoff flow energy dissipation efforts to reduce erosion potential;
c. surface drainage channel design criteria;
d. general development restrictions; and,
e. for those facilities which discharge to a sanitary sewer system, a treatment charge may be assessed based on the contaminant load.

POROUS PAVEMENTS

A porous pavement system is an innovative solution to the problem of stormwater drainage and detention from parking and other low traffic areas in the urban landscape. A schematic cross section of a typical porous pavement facility is presented in Fig. 1. This type of pavement can utilize the natural infiltration capacity of the soil to absorb rainfall and local runoff after accumulation in a porous base consisting of sand or large diameter open graded gravel. If infiltration into the soil is undesirable or not practical, lateral drainage to a sump or channel can be provided. This type of pavement can be designed to minimize changes in the runoff characteristics of a watershed during and after development.

In regular applications for highway and airport runway construction, a commonly used porous pavement surface has been referred to as plant mix seal coat, open graded mix, gap graded mix, popcorn mix, or porous friction course. This material consists of an open graded asphalt and concrete mixture with a high percentage by weight of aggregate larger than a number four seive (0.25 in (0.6 cm) in diameter), laid to a thickness of ½ to 1 inch (1.3-2.5 cm). The resulting paving has a coarse surface texture and a high void ratio resulting in temporary storage of surface water while maintaining the coefficient of friction between a vehicle tire and pavement at values



L	length of pavement
W	width of pavement
D	depth of base layer
S_b	slope of base layer
i_r	rainfall intensity
i_s	infiltration rate
d_b	depth of water in base layer
Q_s	surface discharge
Q_b	collection drain discharge

Figure 1. CROSS SECTION OF TYPICAL POROUS PAVEMENT FACILITY

comparable to the coefficient under dry conditions. The open graded asphalt concrete underlain by a gravel base course with appreciable storage capacity is another type of porous pavement. The whole system can be isolated from the natural ground by an impermeable boundary such as a concrete block wall or a polyethylene liner, in which case some type of artifical drainage would be needed; or, the porous pavement system may be allowed to drain into the natural ground at all points of contact. The latter arrangement does not preclude the use of supplemental drains, necessary in the case of natural ground with low permeability. Where storage is provided, flow control devices may be incorporated to regulate the release, e.g., to prevent discharge during a predetermined period after a storm event.

Parking lots consisting of lattice work concrete blocks with grass planted in the interstices are an aesthetic and practical solution to urban stormwater drainage and detention. Parking areas with occasional use and low driving speeds would allow for the growth of grass or other vegetative cover. In heavier use areas, the ground surface within the lattice blocks may be lower than the concrete surface so that the grass is kept trimmed but not worn out by traffic passing over it. This design also allows for storage of runoff in the low areas within the blocks, and permanently removes that volume of water from surface discharge. Furthermore, the grass may provide an added benefit in being able to recycle nutrients and other runoff constituents.

By design, several inches of rainfall and runoff can be stored within the porous pavement facility prior to discharge via infiltration into the natural soil or through a collection drain. The pavement can be designed to retain all of the rainfall and runoff with no drainage from the site, to retain sufficient rainfall and runoff to reduce the after-development hydrologic conditions to predevelopment conditions, or to delay runoff from the site, thus attenuating peak discharges and reducing the impact of associated pollutant transport. Any combination of these properties can be incorporated into an overall project drainage design to satisfy municipal or watershed drainage management criteria.

Pollutant removal mechanisms in a porous pavement system have not been fully documented. The relatively slow hydrodynamics may allow some settling of suspended matter. Adsorption to and absorption in the base media may also be realized. Although transport of soluble constituents into the ground via infiltration removes them from the porous pavement facility, groundwater transport to receiving waters may result.

PROJECT INFORMATION

An earlier study summarized design and construction of existing porous pavement types and presented design and operational criteria that could be implemented for an efficient and adequate porous pavement project (1). However, several issues, including maintenance, durability, and economic, hydrologic and environmental benefits, remained unresolved.

This study, as reported herein, provides some of this information and extends the design and operational criteria a step further by providing a design procedure which is relatively simple to understand and apply, and has minimal computational and data requirements. Four specific objectives were addressed in this project:

1. To determine the stormwater hydrologic and water quality characteristics of porous pavements and to compare these characteristics to nonporous pavements.
2. To determine the relative capability of porous and nonporous pavements to assimilate or reduce typical pollutants in urban runoff through storage and percolation.
3. To evaluate the performance of porous pavement systems with various physical characteristics under a range of storm conditions.
4. To develop a design methodology for porous pavements which can be used by engineers, planners, and building plan reviewers to estimate facility performance at proposed development sites.

SECTION 2

CONCLUSIONS

In a previous study a comprehensive literature review was conducted to assess the "state of the art" in open-graded porous asphalt design and construction (1). The literature review established the following:

- Although construction costs data for an open-graded asphalt mix are available, these data are dated and a comparison to conventional dense-graded asphalt construction costs was essentially lacking.
- Construction specifications for open-graded mix design and construction have been suggested by several authors (2, 3); however, a standard, uniform set of specifications for this type of construction was nonexistent.
- The computer model PORPAV simulates the hydraulics of a porous pavement system and as such is a good analytical tool; however, a straightforward approach to the design of simple porous pavement systems with minimal computational and data requirements was lacking.

This project, therefore, concentrated on three principal areas:

- Costs associated with construction of an open-graded porous asphalt parking lot in comparison to conventional dense-graded asphalt construction.
- Development and assessment of a set of standard construction specifications for open-graded porous asphalt pavements (presented in Appendix A).
- Development of a standard methodology for design of porous pavement systems.

The investigations led to the following conclusions:

1. *Based on the Austin experience, porous asphalt construction costs are comparable to costs for conventional asphalt construction.*

The Austin experience indicates that a porous asphalt lot incorporating a storage reservoir can be constructed (including engineering, inspection and testing) for about $10 per square yard ($12 per square meter). In Austin, standard practice in the design and construction of conventional parking lots is to incorporate stormwater detention into the parking lot area with a six-inch (15 cm) curb and restricted outlets. Construction cost for this type of conventional system is about $8.50-$8.75 per square yard ($10.00-$10.50 per square meter). If engineering, inspection and testing are added to this (assuming 17 percent of the construction costs) the total cost is again about $10 per square yard ($12 per square meter) or equivalent to the porous asphalt lot. Should the site specifics (i.e., topography, size, slope, ect.) necessitate site grading or an offsite detention structure, the conventional system cost would, of course, be higher.

2. *In compaction of the porous asphalt pavement, the type of compaction is less important than compacting the surface at a temperature near 180 F (82.2 C).*

It was apparent from this project that conventional mixture temperatures in the order of 260 to 280 F (126.7 to 137.8 C) should be used for laydown, but that compaction should be delayed for this type of mixture until it had cooled down near 180 F (82.2 C). If this approach is followed, the material placement should be easily effected and a stable surface produced with the desired porosity.

The apparent success in densifying the surface course using six passes of an 8-ton (7.3-metric ton) pneumatic roller, four passes of an 8-ton (7.3-metric ton) pneumatic roller, one pass of a 1-ton (0.9-metric ton) pneumatic roller, and a combination of first pass with the 1-ton (0.9-metric ton) flat-wheel tandem roller followed by the heavier pneumatic roller appeared to indicate that light compaction equipment should be used, but that a reasonable surface can be attained in a variety of ways as long as the mixture is not too hot when compacted.

3. *The tensile strengths of the open-graded porous hot mix asphalt concrete (HMAC) cores are lower than for conventional dense-graded HMAC cores.*

Tensile strengths for asphalt concrete mixes are considerably affected by the temperature of the mix. The porous asphalt mix varied in strength from an average of 185 psi (13 kg/cm^2) at 40 F (4.4 C) to an average of 70 psi (4.9 kg/cm^2) at 100 F (37.8 C). As expected, the indirect tensile strengths of the porous asphalt cores are lower than those of typical dense-graded HMAC cores. The strengths at lower temperatures are still relatively high, however, and those at the most critical higher temperatures did not vary greatly from those for dense-graded mixes. The greatest relative difference between the porous asphalt and dense-graded mixes occurred in the middle range of temperatures near 70 F (21.1 C). The indirect tensile strengths for the porous asphalt cores did not vary greatly between 70 and 100 F (21.1 and 37.8 C), so that the minimum tensile strength within the range of temperatures was on the order of 60 psi (4.2 kg/cm^2) or greater. This compares with the 85 psi (6.0 kg/cm^2) average at 100 F (37.8 C) for HMAC cores. It appears then that the strength of the porous asphalt is greater than anticipated as compared to dense-graded mixes, and that it may be expected to be reasonably stable.

4. *The computer simulation program PORPAV, herein revised, can be used to estimate the stormwater hydraulic response of both porous and nonporous pavement facilities.*

5. *The design methodology developed during this study is an effective tool for preliminary design of a porous asphalt facility.*

The design methodology offers a straightforward approach to the preliminary design of simple porous pavement systems with minimal computations and data requirements. The versatility of the methodology allows its application to various design objectives, including:

- a wide range of site and design storm characteristics;
- sizing the pavement facility for volume or discharge limitations;
- the option of using an impermeable boundary to prevent leakage; and,
- the option of utilizing a collection drain within the porous base.

Although the methodology has not been applied to the actual design of a pavement facility, confidence in its effectiveness stems from the use of PORPAV in simulating stormwater hydraulics; the flow governing equations utilized in PORPAV were incorporated into the design methodology.

SECTION 3

RECOMMENDATIONS

1. The use of PORPAV by municipal utilities and other planning agencies is recommended to evaluate the stormwater hydraulic response of proposed pavement facilities.

2. The design methodology developed during this study has not been applied to an actual stormwater storage system design and its use in the field is recommended to thoroughly identify and ameliorate any inherent limitations.

3. If the user has access to computer facilities, it is recommended that the program PAVDES, developed in this study, be utilized to increase the efficiency of the porous pavement design procedures. If desired, PORPAV can subsequently be executed with the resultant design values to simulate the pavement hydraulic response to a variety of storm event conditions. Used alone, PORPAV may be utilized as a design tool as well, although iterative executions are required to determine the optimal pavement design.

4. Where municipal and watershed ordinances allow onsite depression storage on a pavement surface, use curbs in conjunction with porous asphalt pavement to increase hydrologic and water quality benefits. The presence of depression storage on impervious pavements appeared to provide a positive benefit for stormwater contaminant control. Periodic vacuum sweeping would remove accumulated contaminants and prevent their possible resuspension and discharge from subsequent stormwater scouring.

5. A compilation of information on the intensity, frequency and complexity of maintenance as well as the useful life for various porous pavement facilities, is needed.

6. When employing gravel trenches using a small diameter gravel filter course, an elevated curb should be incorporated to prevent surface runoff on the back side (away from the pavement). The permeability of this filter layer in the gravel trench in this study was exceeded by surface runoff and a portion of the runoff volume bypassed the trench. An alternative recommendation is to not use the small diameter filter course, which has a tendency to become clogged with silt.

7. The rapid response time of the study pavements and the stochastic nature of storm events made sampling natural precipitation events quite difficult

and labor and cost intensive. As an alternative, future studies of this type should generate runoff events with sprinklers or other rainfall simulation devices.

8. Difficulties were encountered in obtaining uniform water distribution and accurate volumetric measurements when using the sprinkler network to simulate rainfall. For future simulated rainfall studies, use a greater sprinkler and rain gage density, as well as an in-line flow meter to gage the total inflow to the study pavement.

9. Investigate the use of a Venturi-type flume, such as the Parshall flume, rather than a weir as a hydraulic control element for monitoring lot discharge. These flumes have the advantage of a lower head loss than a weir and smoother hydraulic flow, thereby preventing deposition of solids such as was experienced in this study.

SECTION 4

STUDY APPROACH

OVERVIEW

An extensive monitoring program was initiated to document the hydraulic and pollutant transport characteristics of several porous and conventional pavement facilities. A monitoring network of six parking lots was selected, representing a variety of pavement surfaces:

A. Porous surfaces
   1. Porous asphalt
   2. Lattice block with sandy loam
   3. Gravel trench receiving runoff from a conventional asphalt lot
   4. Grass lot

B. Nonporous surfaces
   5. Conventional asphalt
   6. Conventional concrete

Three stormwater sampling surveys were attempted at the grass lot. However, the rapid response time of the small catchment area combined with the difficulty of surface runoff containment created logistical problems which did not warrant further use of the project's labor and materials resources. Hence, the grass lot was removed from the monitoring network.

In addition to three existing lots, numbers 2, 5, and 6 above, a porous asphalt parking lot was constructed. A detailed discussion of the construction process is presented in Section 5. Also, the gravel trench lot was created by installing a narrow gravel-filled trench across the downslope width of an existing conventional asphalt lot.

After identification of site locations, construction of the porous study sites, storm sampling and data analysis were conducted. A computer based data storage and plotting package was developed and implemented to compile all data from this project. Detailed discussions of the water quality analysis and model calibration and verification are presented in later sections of this report. The data collected during this study and the resulting model calibration and verification effort provide an insight into the capabilities of PORPAV and its potential application to future studies where similar porous pavement projects are desired.

TOPOGRAPHIC AND CLIMATIC CHARACTERISTICS OF AUSTIN, TEXAS

Austin is the state capital of Texas and is located on the Colorado River at the intersection with the Balcones Escarpment, a major physiographic feature which is a boundary between the Texas Hill Country to the west and the Blackland Prairies to the east. Elevations within the city vary from 400 ft to 900 ft (125 m to 275 m) above sea level. In an east-west direction, the City of Austin spans approximately seventeen miles. Along its northeast-southwest axis, the city measures approximately eighteen miles. The latitude of the City Municipal Building at Eighth and Colorado Streets is 30° 16' 14" and the longitude is 97° 44' 34".

The mean annual temperature is 68.1 F (20.1 C). Winters are mild, with the daily maximum temperature in January, the coldest month, averaging 60.0 F (16.0 C). Below-freezing temperatures occur on an average of only 23 days each year. Rather strong northerly winds in association with cold fronts occasionally accompany sharp drops in temperature during the winter months. However, cold spells are usually of short duration, rarely lasting more than a week. The average length of the warm season (freeze-free period) is 270 days. Based on data from 1943-1961, the mean date of the last occurrence of freezing temperatures in spring is March 3; the first fall occurrence of 32 F (0 C) can be expected on or around November 28. Previous records show that freezing temperatures have occurred as late as April 13 (1940), and as early as October 26 (1924). Daytime temperatures in summer are hot, with the mean daily maximum reaching 95.9 F (35.5 C) in August. Summer nights are usually pleasant, with minimum daily temperatures in the low seventies.

Average annual rainfall in the Austin area is 32.49 in (82.5 cm). Precipitation is fairly evenly distributed throughout the year, with heaviest amounts occurring in late spring. A secondary peak of seasonal rainfall occurs in September. Precipitation from April through September usually results from convective thundershowers, with fairly large amounts of rain falling within short periods of time. While thunderstorms and heavy rains occur in all months of the year, most winter precipitation falls as light rain. August is the driest and hottest month. Snow is insignificant as a source of moisture and usually melts as rapidly as it falls; the city may experience several seasons in succession with no measurable snowfall.

Prevailing winds are southerly throughout the year. Northerly winds accompanying the colder air masses in winter soon shift to southerly as these air masses move out of the Central Texas region. Destructive winds and damaging hailstorms are infrequent. On rare occasions dissipating tropical storms affect the city with strong winds and heavy rains. On the average, 133 days are cloudy each year, 117 days are partly-cloudy and 115 days are clear. Austin usually enjoys 61 percent of maximum possible sunshine annually.

DESCRIPTION OF STUDY SITES

The locations of the five types of parking lot pavement surfaces selected for monitoring are shown in Fig. 2. A summary of physical characteristics of the study lots are presented in Table 1. The following text discusses the physical characteristics and sampling procedures for each study lot.

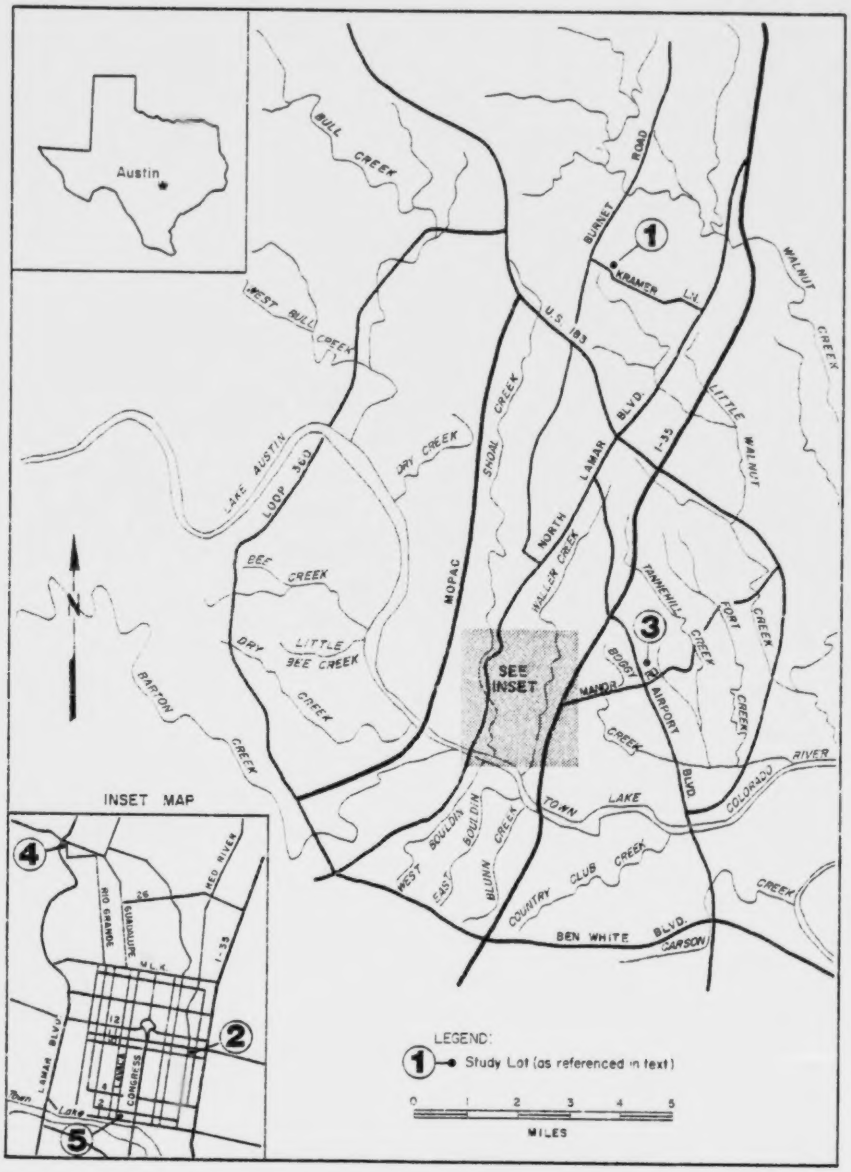


Fig. 2. Study Lot Locations

TABLE 1

PHYSICAL CHARACTERISTICS OF THE STUDY LOTS

Fig. 2 Ref. No.	Pavement Surface	Area Location	Slope (acres)	Parking (percent)	Spaces	Traffic* (vehicles per day)
1	Porous asphalt	city maintenance yard	0.354	(surface) 0.0 (base) 2.6	20	10
2	Lattice block	Symphony Square	0.143	4.0	14	14
3	Gravel trench at asphalt lot	airport rental car storage	1.364	5.0	186	375
4	Conventional asphalt	Sr. Citizen's Activity Center	0.255	3.9	33	100
5	Conventional concrete	City Hall Annex	0.369	1.1	35	70

1 acre = 43,560 square feet = 4,047 square meters

* Estimated from the number of parking spaces and field observations of approximate daily occupancy rates.

Porous Asphalt Lot

A comprehensive discussion of the design and construction of the porous asphalt parking lot is presented in Section 5.

A plan drawing and photograph of the porous asphalt study lot are presented in Fig. 3 and 4, respectively. The porous asphalt lot consisted of a surface asphalt layer and two layers of stone on top of an impervious limestone bedrock base. The base layer was made up of a stone course with rocks ranging from 1.5 to 2.5 in (3.0-6.5 cm) in diameter. This base ranged in depth from approximately 4 in (10 cm) on the upslope end to 42 in (107 cm) on the low end and provided a void space of approximately 35 percent of its volume for water retention. The second layer averaged 2 in (5 cm) in depth and consisted of a stone top course (filter course) with material ranging from 0.4 to 0.6 in (1.0-1.5 cm) in diameter. This intermediate layer was selected to provide a stable and uniform surface for the application of the porous asphalt. The final layer consists of a 2.5-in (6.4 cm) thick porous asphalt and concrete mix with 5.5 to 6.0 percent asphaltic content by weight.

The original design called for runoff to be monitored within a collection basin located at the downslope corner of the lot. A 6-mil (0.015 cm) polyethylene impermeable liner was installed along the above-grade downslope width and side to prevent seepage. However, this seal leaked and the base discharge did not flow into the monitoring barrel. Small trenches and berms were constructed along the periphery of the lot to ensure all runoff was captured. A 90-degree V-notch weir was installed below the lot to measure the discharge rates. Visual stage readings by the field crew were used as a basis for the runoff calculations. Water quality samples were obtained at the weir.

Lattice Block Lot

A plan drawing and photographs of the lattice block lot investigated in this study are presented in Fig. 5 and 6 (a and b), respectively. The interstices of the lattice blocks were filled with sandy loam and planted with bermuda grass, as characterized in Fig. 7. Runoff was monitored through a 3.5 x 1.5 x .75 ft (1.1 x 0.5 x 0.3 m), 90-degree V-notch weir in conjunction with a staff gage at the weir. The weir and staff gage were located within a catch basin with an access manhole. Water quality samples were obtained at the weir.

Gravel Trench Lot

A plan drawing and photographs of the gravel trench lot are presented in Fig. 8 and 9 (a and b), respectively. The study area consisted of a conventional asphalt lot with a 4-ft (1.2-m) wide drainage trench, ranging in depth from 2 to 4 feet (0.6 to 1.2 m) across the downslope width. The trench was lined with a 6-mil polyethylene sheeting and filled with 1.5 to 2.5 in (3.8-6.4 cm) diameter crushed stone which had been cleaned and washed. This base was topped with approximately 1 ft (30 cm) of smaller than 1-inch (2.5-cm) diameter gravel. The trench was subsequently flushed with several volumes of water to rinse out construction fines. Stormwater flows within the drainage trench were monitored within a 55-gallon (208-l) barrel. A 4-in (10-cm) diameter pipe was used as the discharge control. All discharges were

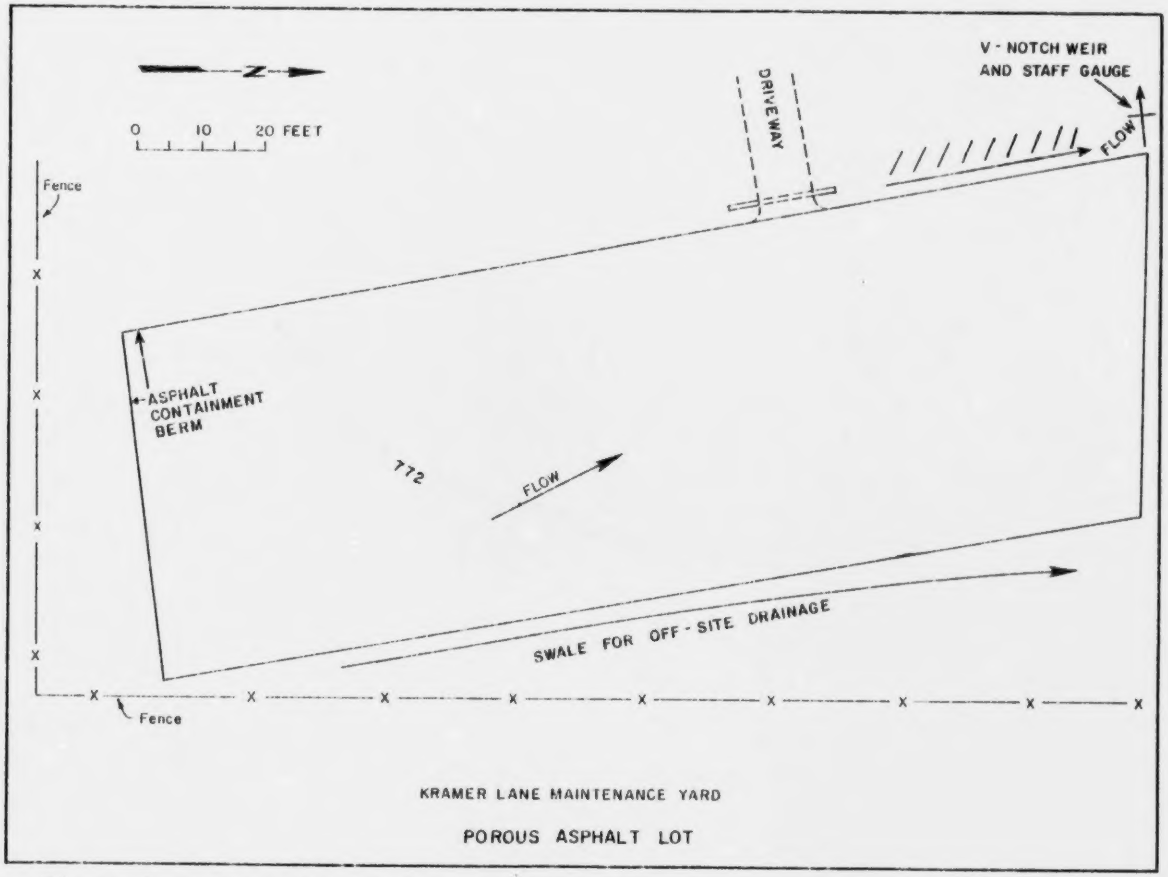

N
0 10 20 FEET
Fence
DRIVEWAY
V - NOTCH WEIR AND STAFF GAUGE
FLOW
ASPHALT CONTAINMENT BERM
772
FLOW
SWALE FOR OFF - SITE DRAINAGE
Fence
KRAMER LANE MAINTENANCE YARD
POROUS ASPHALT LOT

Figure 3. Plan View of Porous Asphalt Lot.

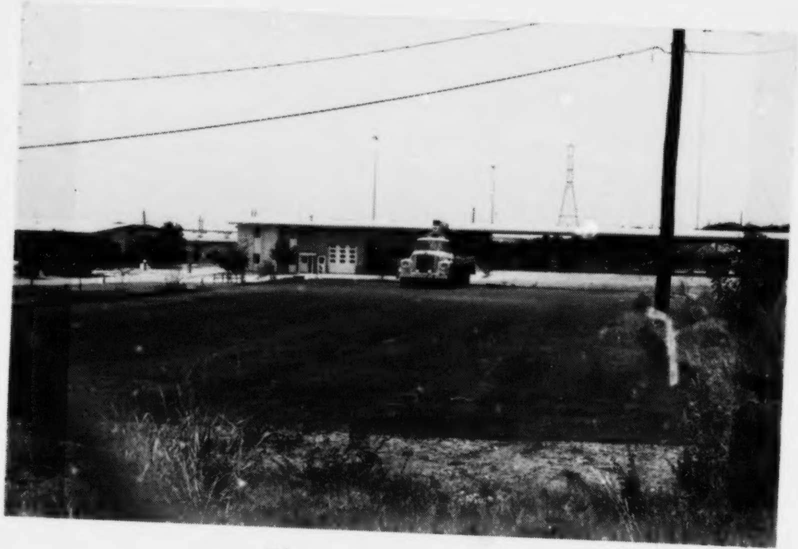


Figure 4.
Porous Asphalt Lot.
Large Truck is Typical of
Equipment Parked on This Lot.

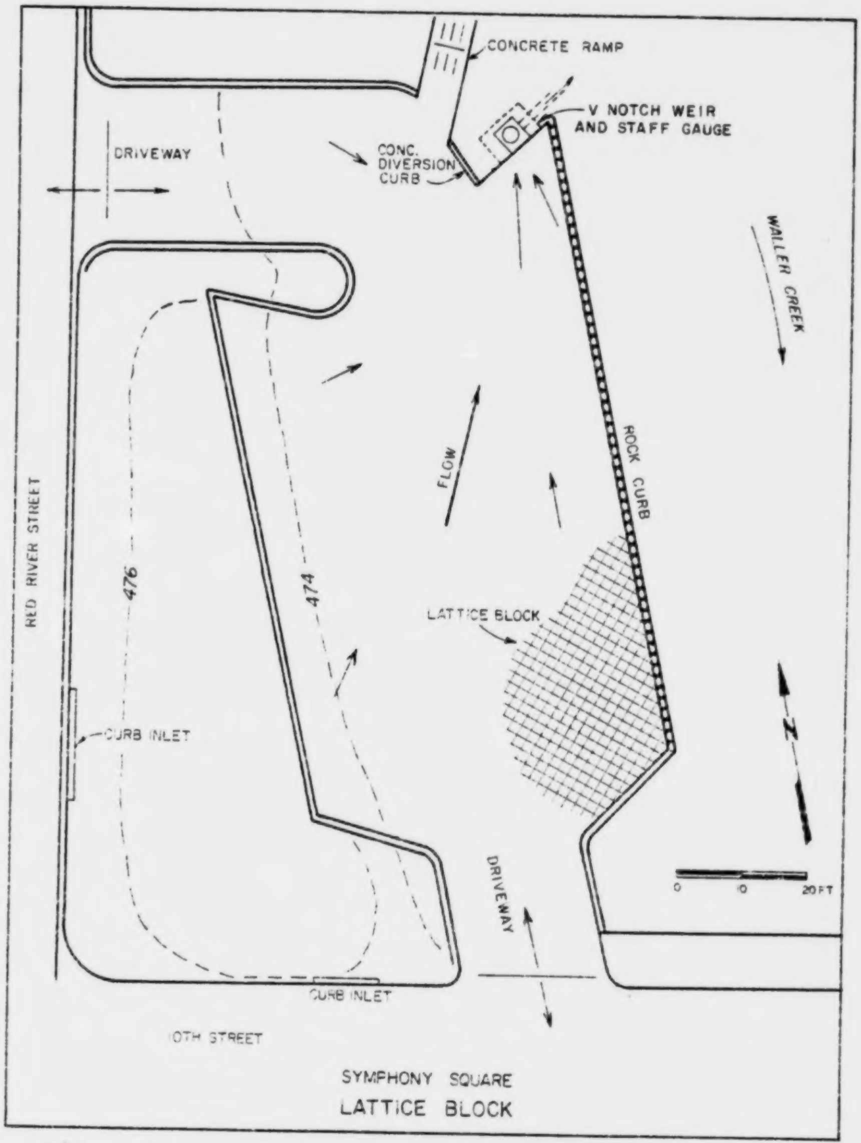


Figure 5. Plan View of Lattice Block Lot.

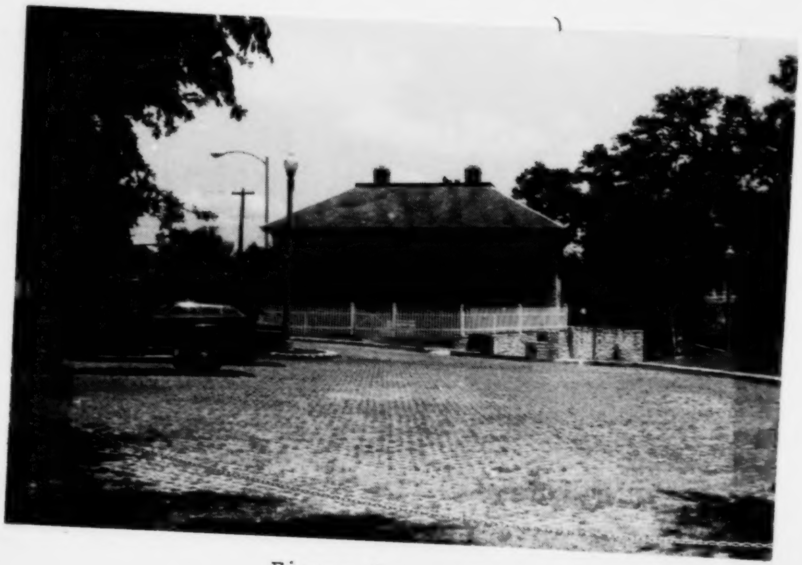


Figure 6a.
Concrete Lattice Blocks.

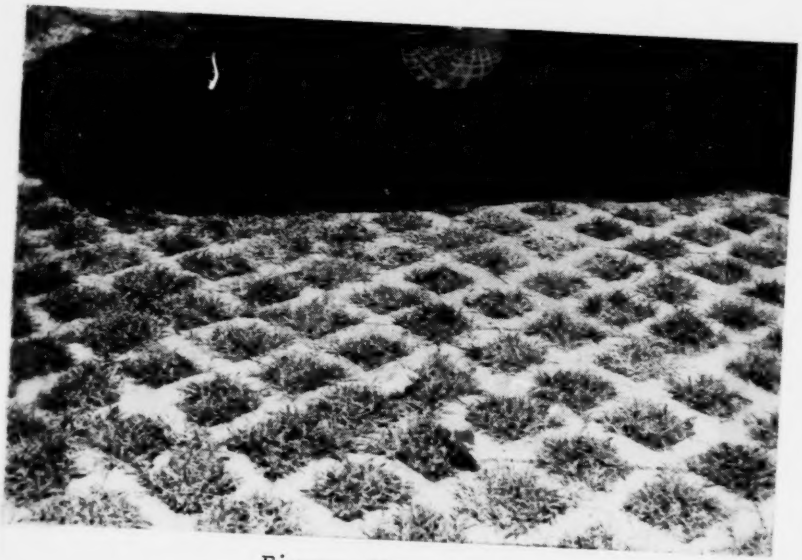


Figure 6b.
Closeup of Lattice Blocks
Showing Grass Growing in Interstices.

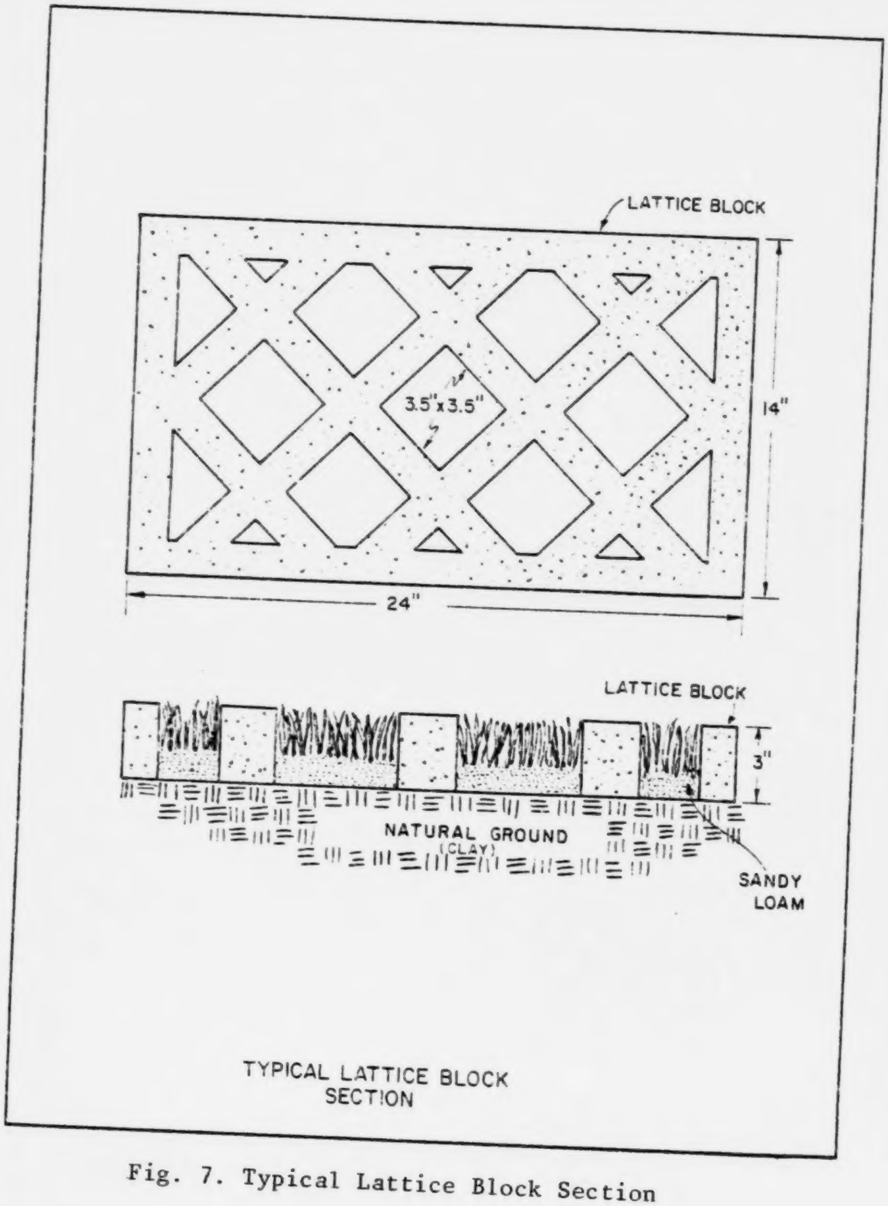


Fig. 7. Typical Lattice Block Section

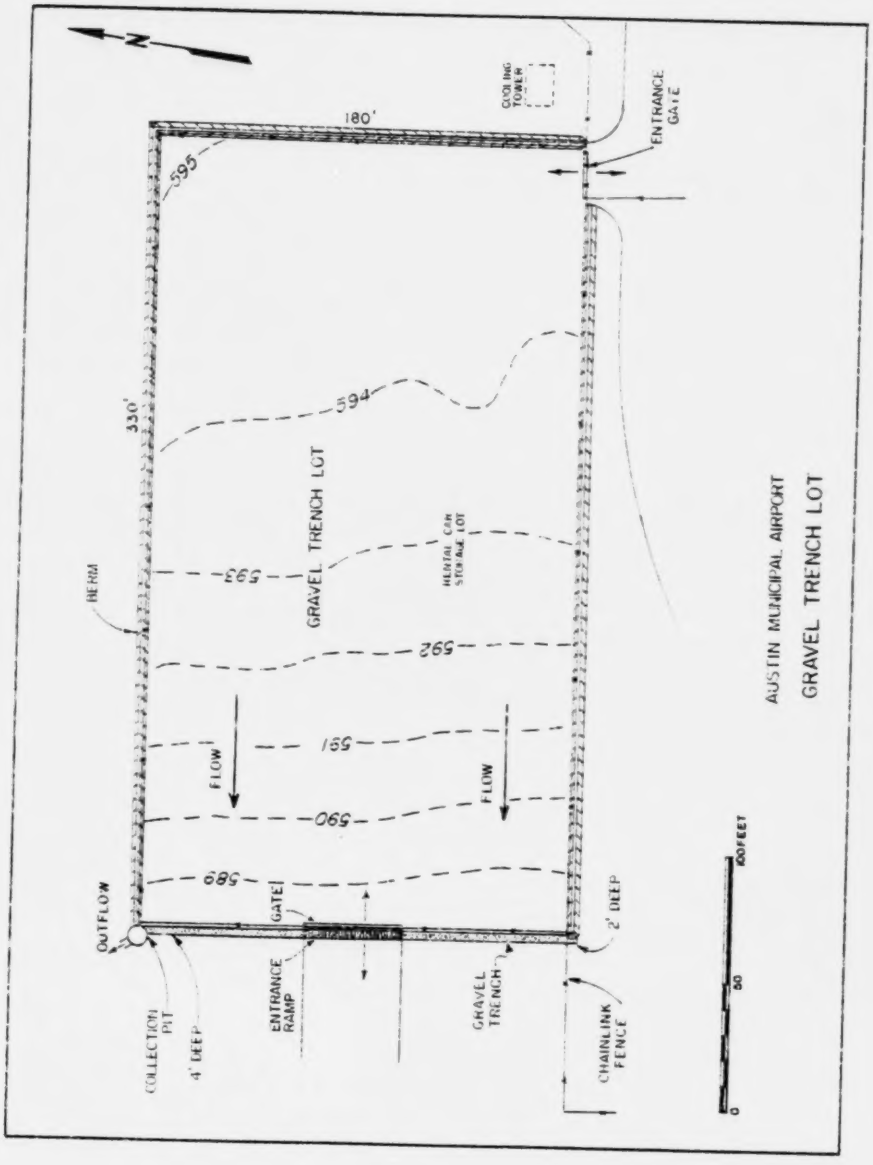


Fig. 8. Plan View of Gravel Trench Lot.

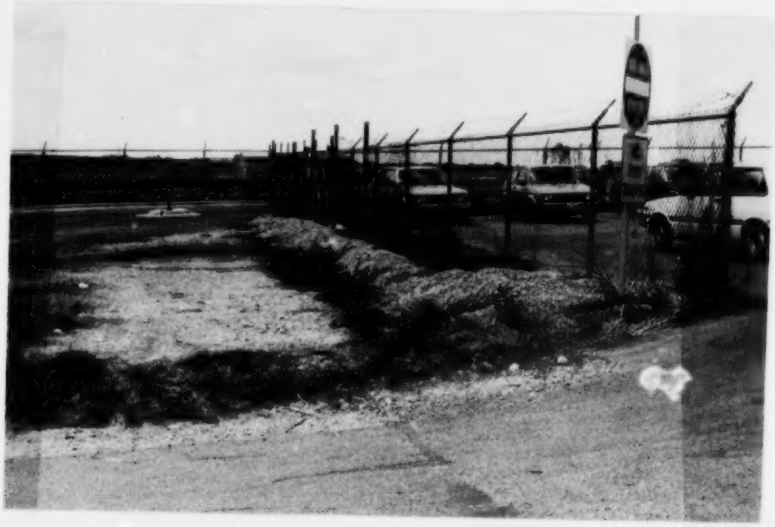


Fig. 9a. Gravel Trench Lot.

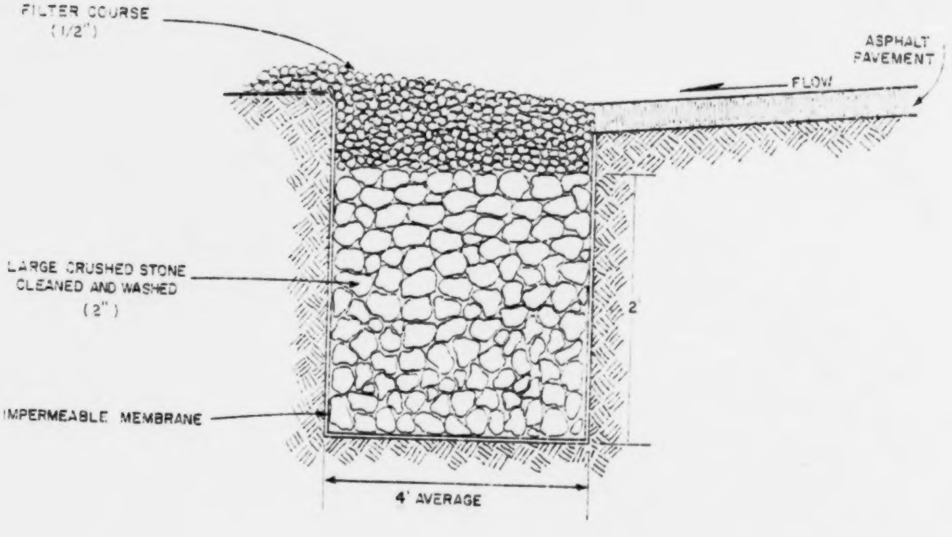


Fig. 9b.
TYPICAL SECTION
FOR GRAVEL TRENCH.

calculated based on readings of the water level taken by the field crew from a staff gage located within the barrel.

Conventional Asphalt Lot

A plan drawing and photograph of the conventional asphalt lot monitored in this study are presented in Fig. 10 and 11, respectively. Runoff discharge was estimated from water levels in a 3 x 3 x 1.5 ft (0.9 x 0.9 x 0.5 m), 90-degree V-notch weir. Rainfall amounts during the natural storm events were obtained from a NWS standard 8-in (20-cm) weighing bucket recording gage located within 100 yds (91 m) from the site. Water quality samples were collected at the inlet to the weir.

Conventional Concrete Lot

A plan drawing and photograph of the conventional concrete lot are presented in Fig. 12 and 13, respectively. Runoff volumes were estimated by staff gage readings of the water level behind a 90-degree V-notch weir. Rainfall amounts were measured using a National Weather Service (NWS) standard 8-in (20-cm) weighing bucket recording gage situated on top of the City Hall Annex, located within 100 yds (91 m) from the lot. Water quality samples were obtained at the discharge from the weir.

METHODOLOGY

The meteorological staff of Espey, Huston & Associates, Inc. was relied on heavily for preparing forecasts and radar interpretations of local weather to provide the field crews with adequate lead time to be at a sampling site when rainfall began. The small areal size of the study lots resulted in rapid catchment responses to a rain event, providing a narrow time window for a successful sampling survey.

During the 26 months of sampling, beginning in April 1980, the National Weather Service (NWS) office in Austin recorded 16 months of below normal precipitation. However, for the same period, Austin was 7.02 in (17.83 cm) above normal. Three anomalous storms in May and June 1981, totaling 14.04 in (35.66 cm), accounted for this excess in rainfall. Without these three storms Austin would have been 7.02 in (17.83 cm) below normal. Forecasting precipitation for single parking lots is a formidable, if not impossible, task and discretion was used in making city-wide predictions. The lack of appreciable rainfall and the rapid runoff response time of the lots were prime considerations for the decision to proceed with simulated rainfall testing.

Sprinkler-induced "storms" provided the ability to control the intensity, duration and timing of the rainfall events which was impossible with the natural events. Sufficient antecedent dry periods were allowed between tests to allow an accumulation of pollutants on the pavement surfaces. Impact-type sprinklers, supplied by the City of Austin Parks and Recreation Department, were used during the test with the City's fire hydrants used as the source of water. A schematic of the sprinkler arrangement is provided in Fig. 14. The number of sprinkler heads was varied for each simulated storm and care was taken in placement of the heads to provide uniform coverage of the lot. Equivalent rainfall estimates were obtained by placing eight wedge type rain gages on wooden stands around the test lot. The rain gage (Fig. 15) used in the simulated storm studies was a wedge type manufactured by TRU-CHEK®

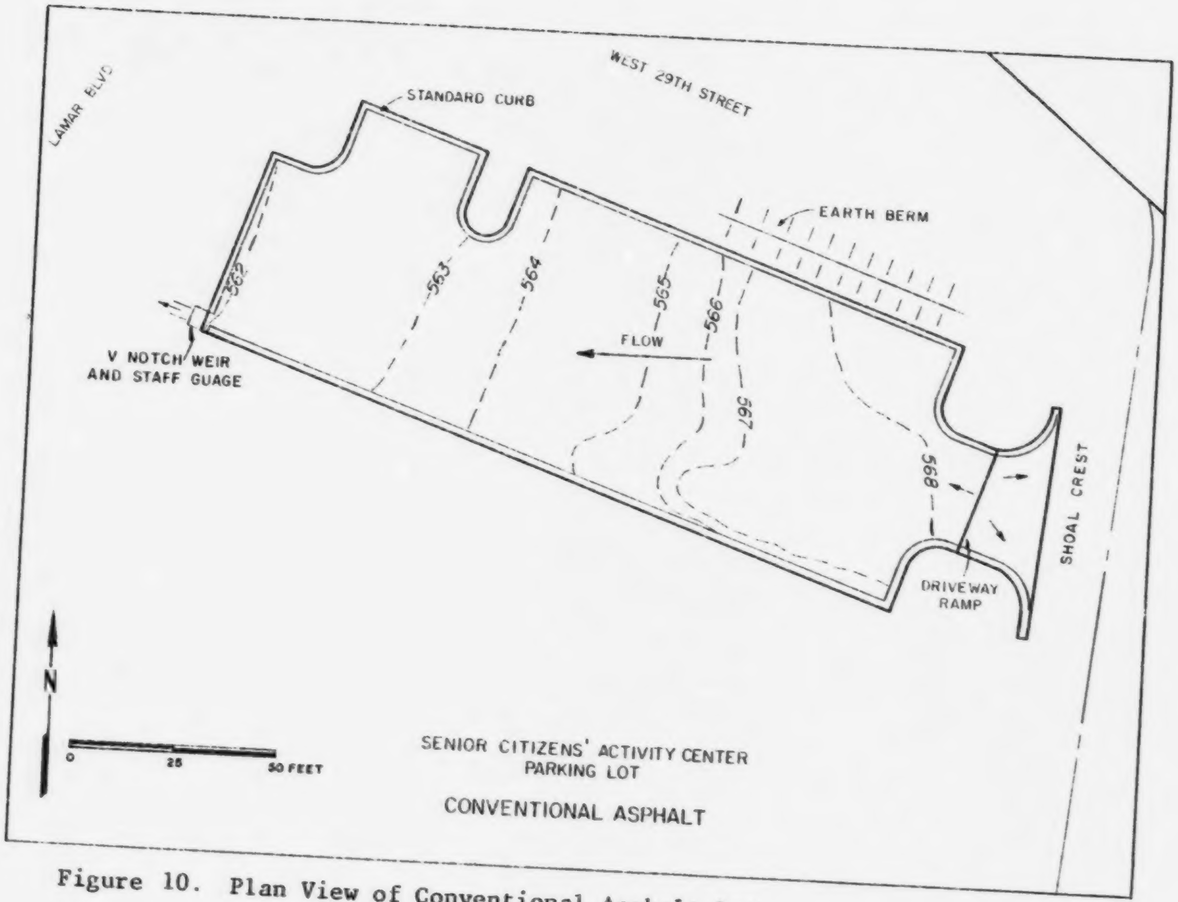


Figure 10. Plan View of Conventional Asphalt Lot.

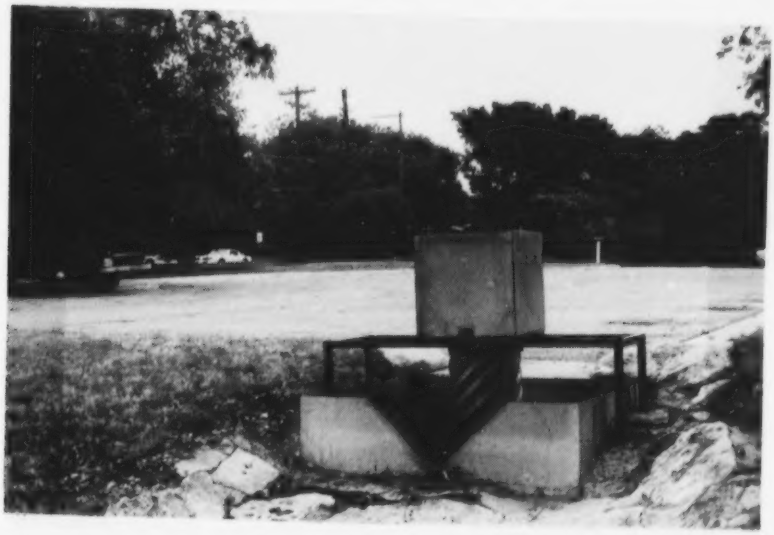


Fig. 11. Conventional Asphalt Lot.

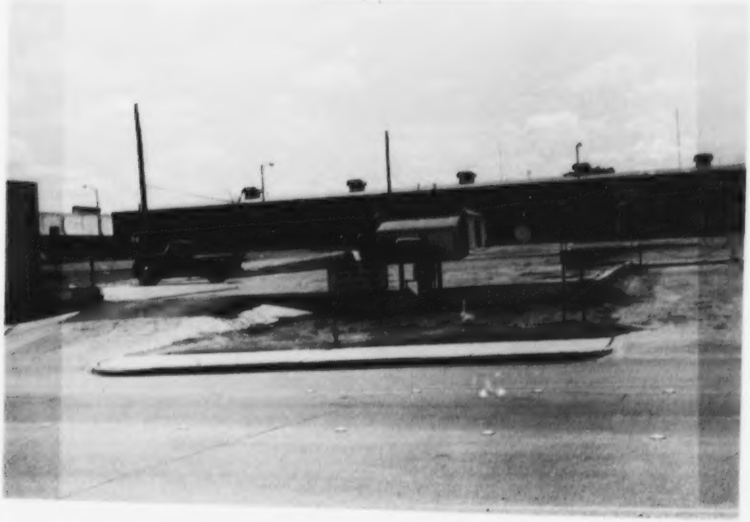


Fig. 13. Conventional Concrete Lot.

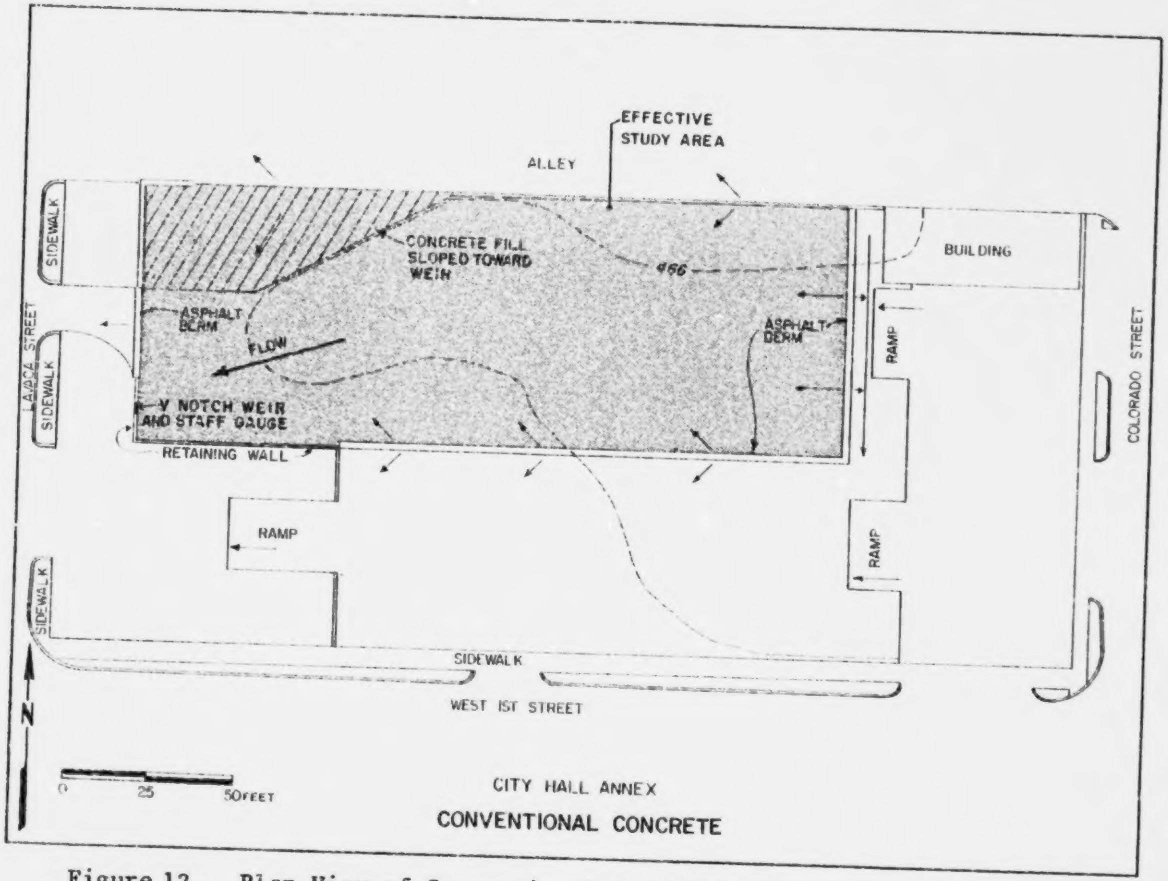


Figure 12. Plan View of Conventional Concrete Lot.

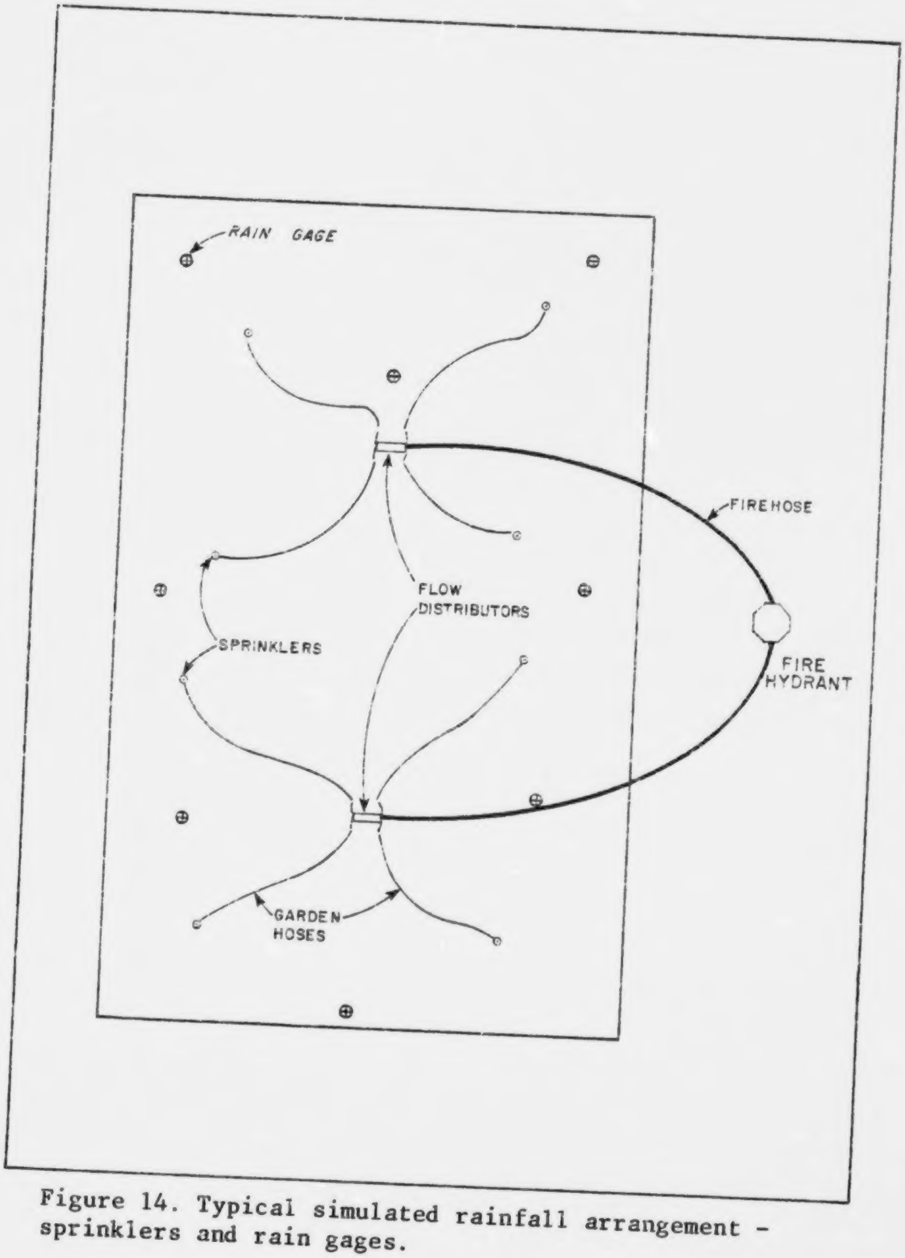


Figure 14. Typical simulated rainfall arrangement - sprinklers and rain gages.

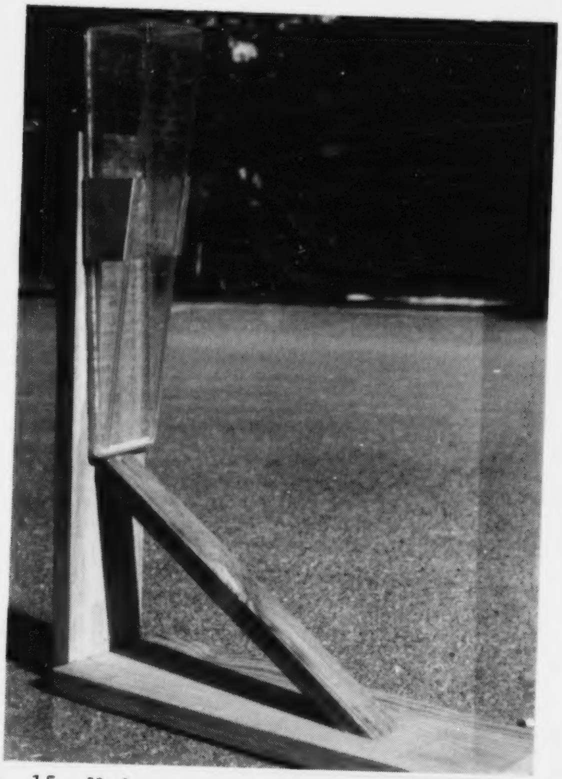


Fig. 15. Wedge-type rain gage used during sprinkler events.

Fig. 16. Water truck used during stormwater simulation.

rain gage division of the Edwards Manufacturing Company, Albert Lea, Minnesota. This gage is calibrated to measure in increments of 0.01 of an inch (0.03 cm) to 6 inches (15 cm). The manufacturer's literature refers to tests made by the American Geophysical Union (4) concluding that the TRU-CHEK® wedged shaped gage produces similar accuracy as the standard 8-inch (20-cm) gage used by the U.S. Weather Service. During the tests, readings of the rain gages were made at regular intervals (every 15 to 30 minutes) and at the conclusion of the event. Once the individual rainfall totals were compiled, the values were averaged to provide an approximation of the total event volume. Average intensities varied from 0.3 in/hr (0.8 cm/hr) to 1.9 in/hr (4.8 cm/hr). As a comparison, an analysis of long-term (1947-1972) hourly rainfall recorded at the Austin airport yielded the intensity characteristics of Austin precipitation events presented in Table 2 (5).

The gravel trench lot was too large for sprinkler coverage, so 2000-gallon (7600-l) capacity rear-end-dispensing water trucks provided by the City of Austin were used (see Fig. 16). The trucks drove slowly across the upper end of the lot releasing water at approximately 300 gallons per minute (19 l/s). Different event intensities were obtained by varying the number of trucks used, trips made, and number of trucks releasing at one time.

Runoff discharge estimates were obtained from water level measurements at a 90-degree V-notch weir at each lot except for the gravel trench lot, which incorporated a collection basin with an outflow pipe. Staff gages were installed beside the weirs and outflow pipe to monitor the intraevent hydrograph progress. The visual stage readings were used as a basis for discharge estimates, utilizing the standard flow equation for a 90-degree V-notch weir and the orifice equation for the outlet pipe at the gravel trench lot (6).

Sample collection, handling, and analytical techniques employed in the study conform to recommended EPA or American Public Health Association methodology (7, 8, 9 and 10). The parameters tested and specific methodologies used are shown in Table 3. Chemical preservatives were employed for certain constituents (e.g., nitric acid was added for metals preservation) and appropriate sample containers were utilized (7, 8 and 9). All samples were placed on ice after collection and delivered to laboratory personnel within the limits of EPA recommended holding times for the samples (7, 8 and 9). Laboratory analyses were conducted by the Guadalupe-Blanco River Authority, Seguin, Texas, using EPA approved methods (7).

To determine the potential for ground water contamination from trace organic substances in the runoff from the porous asphalt and grasscrete lots, analyses of samples taken during simulated rainfall tests were made for volatile and semivolatile priority pollutants. Laboratory analyses were conducted according to EPA methodology (8 and 9).

SIMULATION OF STORMWATER HYDRAULICS

Prediction of hydraulic characteristics is a valuable tool for assessing the performance of stormwater runoff control strategies. Stormwater hydraulic characteristics of the porous and nonporous pavement study sites were evaluated using the computer model PORPAV (herein modified), which is described in a previous report (1). PORPAV is a two-dimensional dynamic water budget analysis of a pavement facility.

TABLE 2

INTENSITY CHARACTERISTICS OF AUSTIN RAINFALL

Intensity (in/hr)	Occurrence Interval (months)
0.79	
1.59	1
2.28	4
3.19	6
	12

Source: Hydroscience, 1976 (5)

1 in/hr = 2.54 cm/hr

TABLE 3

LABORATORY ANALYTICAL METHODS

Parameter	Reported as	Specific Method
BOD_5	BOD	Electrode
COD	COD	Dichromatic Reflux
Fecal Coliform[1]	No./100 ml	Membrane Filter
Oil and Grease[1]	Freon Extractables	Gravimetric
Total Suspended Solids	TSS	Gravimetric
Volatile Suspended Solids[1]	VSS	Gravimetric
Nitrate Nitrogen	N	Cadmium Reduction
Total Kjeldahl Nitrogen	N	Digestion
Total Nitrogen	N	Summation of TKN & NO_3
Total Phosphorus[1]	P	Ascorbic Acid Reduction
Cadmium[1]	Cd	Atomic Absorption
Copper[1]	Cu	Atomic Absorption
Lead	Pb	Atomic Absorption
Zinc	Zn	Atomic Absorption

[1] Analysis for these constituents was discontinued at the end of 1981.

The utilization of PORPAV allows a comprehensive analysis of flow and storage in porous and nonporous pavement facilities, facilitating comparisons of the hydraulic response of alternative pavement designs. The computational scheme of PORPAV is described below.

The rate of inflow to the pavement facility from rainfall and, if present, any contributing area is compared to the permeability of the porous pavement surface for each time interval. For porous systems in general, the surface permeability is much greater than the inflow runoff rate and all of the water moves into the pavement control volume. For nonporous pavements the permeability is generally less than the runoff rate and a limited portion of the inflow moves into the pavement. The excess is stored on the surface of the pavement for subsequent computation of surface runoff from the pavement.

The inflow into the pavement control volume is added to the existing storage and then compared to the limiting, i.e., lesser, permeability of the pavement and the base layer. If the limiting permeability is greater than the inflow into the pavement, then all of the flow is transferred into the base control volume. This is true for most porous pavement systems operating according to design. In those instances where the limiting permeability is less than the inflow rate, the inflow into the base is computed as the vertical seepage into the base. The difference between the inflow into the pavement and the outflow from the pavement is stored in the pavement control volume.

The inflow into the base control volume is added to the existing base volume and then compared to the permeability of the natural ground. If the bottom is sealed with an impermeable membrane, then no flow is lost to the natural ground. The volume remaining in the base after vertical seepage into the natural ground is subsequently compared to the drain capacity, if present. The difference between the inflow into the base and the outflows (vertical and lateral) from the base is stored in the base control volume.

Stored volumes in each layer are compared to maximum volumes, defined as the product of the depth and porosity. If the maximum volume in the base is exceeded, the excess is stored in the pavement; if the maximum pavement volume is exceeded, the excess is added to the surface storage on the pavement. Surface runoff is then computed as broad channel flow from the pavement.

REVISIONS TO PORPAV

Modifications to PORPAV which were implemented during the current study are discussed below. The program listing for the revised PORPAV is presented in Appendix B. Refer to Fig. 1 and List of Abbreviations and Symbols for a description of a cross section of a typical porous pavement and the identification of the parameters used in the following discussion.

1. Vertical component
    A. The original PORPAV incorporated a variable head permeability equation to calculate the vertical flux between layers. However, this relationship cannot be developed adequately for application in a porous pavement model. The revised PORPAV uses the limiting (i.e., the lower)

permeability of the conterminous layers as the true indication of the vertical flux of water between the layers, subject to storage constraints in both layers. This revision more accurately describes the vertical flux between layers than was included in the original PORPAV.

B. Infiltration Expression

An alternative to the constant infiltration rate previously incorporated in PORPAV was included in the revised PORPAV of the form

$$i_s = i_f + (i_o - i_f)\, e^{-kt}$$

where i_s is the infiltration rate at time t;

i_f is the infiltration capacity (minimum rate) of the soil;

i_o is the initial infiltration rate;

k is the first-order decay coefficient; and,

t is the elapsed time.

This expression is known as Horton's equation and is commonly used to describe the variable rate of infiltration during and subsequent to a single, continuous precipitation event (11). The initial infiltration rate is dependent on the initial moisture condition in the soil. Incorporating this expression for the infiltration rate can result in significantly greater vertical transport calculated during the storm event than by using the constant minimum rate. If a constant infiltration rate is preferred, the initial rate may be replaced by the infiltration capacity of the soil.

C. Intra-layer Flow

The revised PORPAV includes a routing procedure to account for the vertical transport of water within the pavement and base layers, simulating the vertical movement of the wetting front as it passes through the pavement system. In essence, volumes of water, defined by the permeability of the layer and the length of the computational time step, are routed through the depth of the layer. This revision more accurately simulates the vertical flux and storage within the pavement system.

2. Horizontal Component

A. The expression for calculating the horizontal discharge from the porous pavement base was revised to more accurately reflect the nonsteady flow regime in the porous media. Darcy's Law was employed as the governing flow equation (12)

$$Q_b = K_b A\, dh/dx$$

where Q_b is the average horizontal discharge;

K_b is the permeability of the base media;

dh/dx is the energy gradient; and,

A is the cross-sectional area of flow.

The energy gradient was approximated by

$$dh/dx = H/L$$

where H is the total elevation potential, equal to $d_b + LS_b$;
d_b is the depth of water in the base layer;
S_b is the slope of the base layer; and,
L is the normal length of the base layer.

The cross-sectional area of flow was approximated as

$$A = wd_b/2$$

where w is the width of the layer.

This yields

$$Q_b = (K_b w S_b)\ d_b/2 + (K_b w)\ d_b^2/2L$$

or on a unit area basis

$$q_b = c_1\ d_b + c_2 d_b{}^2$$

where

$c_1 = K_b\ S_b/2L$; and
$c_2 = K_b/2L^2$.

The capacity of the subsurface drain, or in the absence of drain pipes, the transmissivity of the adjacent soil can reduce this lateral discharge rate. By adjusting the pipe size and base layer depth, maximum allowable discharge rates can be met. When there is no impermeable boundary present to prevent lateral flux, some horizontal discharge will occur to the adjacent soil. However, this horizontal flux is generally negligible when compared to the vertical component leaving the layer via infiltration because of the much smaller cross-sectional area of flow. Also, the moisture content of the surrounding soil increases during the storm event, thereby reducing the energy gradient between the porous media and the soil. In a narrow, high-wall trench without an impermeable boundary or a drain pipe, the horizontal flux to the soil during the initial period of the storm, before the energy gradient between the base and the soil diminishes, may be of the same order of magnitude as the infiltration. By neglecting the horizontal flux, this assumption represents a conservative case with regard to effective storage volume of the porous pavement system.

3. Surface Runoff

The original PORPAV incorporated Manning's equation for runoff on sloped lots and a broad-crested weir relationship for discharge from horizontal lots. In the revised PORPAV the weir equation was replaced by Manning's equation, with the slope of the energy grade line, S, approximated as

$$S = d_s/L$$

where d_s is the depth of water on the surface above the dead storage depth.

4. Detention Time

Provisions were added to PORPAV to calculate the theoretical detention time provided by a pavement facility. This duration was calculated as the elapsed time between the center of mass (first moment) of the inflow hydrograph (including incipient rainfall) and the center of mass of the discharge hydrograph.

5. Other Additions to PORPAV

A dead storage component may result in the base layer due to physical characteristics of the media, e.g., losses to wetting of dry aggregate or soil, or storage below the invert of the collection drain. The capability to account for this dead storage in the base layer was incorporated in the revised PORPAV. Additionally, average and cumulative inflow, peak and cumulative discharge, and other synoptic discharge hydrograph characteristics are also compiled for each simulation.

SECTION 5

PAVEMENT CONSTRUCTION

BACKGROUND

This section includes the results of a limited review of porous pavements in support of the overall investigation and evaluation of porous and conventional pavement systems in Austin, Texas. The objectives of this task were: 1) literature review of past experiences with porous pavements, 2) review of available aggregate mixes and development of a mix design for the porous asphalt surface course, 3) development of design sections for porous pavement facilities, and 4) development of a tentative set of construction specifications.

This section also includes discussions of the porous asphalt facility constructed during the study, including details of preconstruction planning, installation of the aggregate base layer, placement of the porous asphalt surface course, results of indirect tensile strength testing, in situ permeability results, and results of a visual inspection after 18 months of vehicle use.

SITE SELECTION AND CHARACTERISTICS

Initially a porous asphalt lot was proposed and designed for construction on Lake Austin at Walsh Landing, but this site was abandoned due to a lack of funding by the City of Austin. After investigation of 3 more alternative sites, a temporary lot constructed for employee parking at the truck maintenance facility within the City of Austin's Kramer Lane Service Center was selected. The natural ground at this site consisted of limestone outcrop covered by only a few inches of soil weathered from the parent limestone. The site sloped from southeast to northwest at about 1.5 percent.

DESIGN SPECIFICATIONS OF POROUS ASPHALT MIX

One of the most productive areas of study was a literature review on the asphalt mix design, the design of the pavement section, and construction experience with the open-graded materials required. Two organizations have been primarily involved for the past decade in the development of porous asphalt concretes. One is the EPA which supported projects through the Franklin Institute, that had as their aim the control of stormwater runoff through storage or detention in porous components of parking area pavements (3, 13). The other organization is the Federal Highway Administration (FHWA) which has pursued the development of thin overlays of porous friction course in order to expedite removal of free water from the pavement surface to avoid hydroplaning of automobile tires that may lead to accidents (2). Publications by both of these agencies were reviewed in detail in order that experience from both agencies could be combined to turn out an optimal mix design.

Results of the Franklin Institute work reported by Thelen et al. were important in development of an initial design procedure for porous pavements with the specific goal of detaining urban runoff (13). Thelen et al. drew heavily on previous work by the Asphalt Institute on conventional pavements and mix designs for porous asphalt mixes from the Asphalt Institute and the California Department of Transportation. Heavy emphasis was placed on Marshall stability test results and on resistance to freeze-thaw cycling. For the Austin pavement, an asphalt content of 5.5 percent by weight was selected. Lesser asphalt contents were also stable, but it was found that there was too much asphalt hardening below 4.5 percent asphalt content. The California specification for aggregate was selected because it gave high flow capability, had adequate Marshall stability, and withstood 265 freeze-thaw cycles with no apparent degradation. The California aggregate specification was as follows:

Sieve Size	Percent Passing
1/2" (1.3 cm)	100
3/8" (0.9 cm)	90-100
No. 4	35-50
No. 8	15-32
No. 16	0-15
No. 200	0-3

Porous asphaltic concrete was defined as a graded aggregate cemented together by asphalt cement into a coherent mass, with sufficient interconnected voids to show a high permeability to liquid water.

Other significant findings from the studies described by Thelen et al. (13) are listed below:

1. The properties required of a porous asphaltic concrete were that it be economical, durable, safe under traffic and not deteriorate under weather or traffic.

2. The primary factors in the mix design were that the aggregate be open-graded and consist of a sound crushed stone, crushed slag, or crushed gravel. A minimum of 5.5 percent asphalt cement having a penetration of 85-100 was recommended. The aggregate was not to be subject to excessive stripping as determined by ASTM D1664 (14).

Design procedures were offered in terms of stability under traffic and water storage capacity required.

It should be noted that studies by the Federal Highway Administration indicate that variations in asphalt content have little effect on Marshall and Hveem stabilities or flow values (2). This means that these important design criteria for conventional dense-graded mixes are not effective for selection of asphalt content for open-graded mixes. In short, the criteria applied in the development of these early mix specifications were not truly effective, although the specifications selected apparently proved in subsequent field tests to be reasonably adequate.

A more recent publication by Thelen and Howe reports the results of various field studies on porous asphalt pavements and upgrades the design procedures to include an additional six years of experience and research (3). Seven of the eight existing facilities reported on were in Pennsylvania, Delaware and Maryland. The other is at Woodlands, Texas. Some of the information gleaned from this experience follows:

1. It is important that surface course rolling during construction only be accomplished after the porous asphalt has cooled sufficiently to hold its shape; this will require close control as the precise opposite is general practice for dense-graded asphaltic concrete surfaces. Compaction of the asphaltic surface must be controlled during construction to avoid collapsing the pores. It is desirable to maintain a minimum of 16 percent voids in the porous asphalt surface course.

2. The loss of porosity due to dirt being ground into the surface pores tends to be a permanent loss. It is very important to keep soil off the porous asphalt pavement if at all possible. If detected early, it is possible to clean the surface by brushing, vacuuming, or washing.

3. Damage during freezing rain conditions have not been a problem as long as the pavement drains sufficiently. Freezing rain will not be a problem in the Austin area due to the temperate climate.

4. Shear stress arising from repeated vehicle braking or turning at the same spot may collapse the pores. The porosity loss in this case is generally limited to a few square feet under each wheel.

5. Friction coefficients for tires on porous asphalt surfaces were generally lower than conventional pavement coefficients when dry, but are significantly better during wet weather when the safety hazard is the greatest.

6. At the Woodlands, Texas site, deflections under wheel loads for both porous and conventional pavements were essentially the same for a vehicle traveling 15 and 20 miles per hour (24 and 32 km per hour). The porous pavements, however, deflected more slowly and over a longer distance. Rutting generally was not a problem, except on one parking lot that had been subjected to heavy wheel loads.

In general, pores have remained open in the demonstration pavements except when soil is allowed to plug up the pores or at discrete locations where vehicles repeatedly brake.

Some changes in design and construction techniques were reported by Thelen and Howe (3). The more significant of these are listed below:

1. Because of the scuffing of pavements when the front wheels of stationary cars with power steering are turned, it was decided that harder asphalt should be used in general. For the south, including Texas, an asphalt cement having a 50 to 60 penetration is recommended.

2. The percentage by weight of asphalt was changed to allow a range between 5.5 and 6. The lower limit was selected to assure adequately thick layers of asphalt around the stones and the upper limit is to prevent the mix from leaking asphalt during transport, particularly if it is shipped at a temperature of over 300 F (149 C).

3. The recommended stone base course consisted of aggregates with a maximum size of 2.5 inch (6.3 cm) and a minimum size of 1.5 inch (3.8 cm), which was expected to provide a void space of 40 percent of its volume for water retention.

4. Two inches of gravel top course over the base course was recommended to provide a better surface for application of the porous asphalt surface course. The recommended grading for this course was 5/8-inch (1.6 cm) maximum and 3/8-inch (0.9 cm) minimum to provide an essentially uniform aggregate of approximately 1/2-inch (1.3 cm).

5. The depth of the porous asphalt surface course was reduced to 2.5 inch (6.3 cm).

6. Compaction of the subgrade was controlled to prevent reduction in soil permeability.

The California aggregate specifications for the porous asphalt surface course were retained. The design depth of the stone base course was, of course, again dependent on the volume of water to be stored. Also, a minimum of 2 percent passing the No. 200 sieve was adopted to control the asphalt drainage characteristics of the mixture by effectively increasing the viscosity of asphalt cement. The Franklin Institute and FHWA recommended gradation limits are listed below along with the slightly modified gradation limits proposed for this project (3, 2).

Sieve Size	Percent Passing FHWA	 Franklin Institute	 Gradation Recommended
1/2" (1.3 cm)	100	100	100
3/8" (0.9 cm)	100	90-100	90-100
#4	30-50	35-50	35-50
#8	5-15	15-32	15-32
#16		0-15	2-15
#200	2-5	0-3	2-5

The gradation recommended is essentially that recommended by the Franklin Institute, except that a minimum of 2 percent passing the No. 200 has been included. The reasons for favoring the Franklin Institute experience are as follows:

1. The experience on existing Franklin Institute porous asphalt parking lots has generally been good.

2. The FHWA mix was designed as a thin overlay to be applied over existing pavements, whereas the Franklin Institute mix has been placed in a thicker layer over open-graded base material.

3. The primary objective of the FHWA open-graded asphalt friction course is removal of water from the surface of the pavement to increase friction with tires during inclement weather, while the objective of the Franklin Institute porous asphalt pavement is to provide a porous and stable surface over base materials that essentially function as a stormwater detention basin.

The approach to mix design taken by the FHWA is one aimed at testing the course aggregate to arrive at its "surface capacity"; which includes absorption, superficial area, and surface roughness. All of these properties affect the asphalt content requirements. A simple linear relationship obtained from field experience is then applied to arrive at the percent asphalt that should both provide the cementation required between particles and leave sufficient voids (the FHWA goal is a minimum of 15 percent as compared to the Franklin Institute's goal of 16 percent), while not creating excess asphalt that will drain. The Franklin Institute's mix design goals have been similar, but the approach has been one of simply applying a narrow band of asphalt content of 5.5 to 6.0 percent that has proven effective for the aggregates that they have tested. It was decided that drainage tests such as those described in Reference 2 should be conducted on the mix recommended to establish the sufficiency of the 5.5 to 6.0 percent asphalt content for the crushed limestone aggregates proposed for use. This was considered to be much more direct than implementing the detailed and unusual tests recommended by the FHWA for their open-graded asphalt friction course. It also provided a little more positive approach than Franklin Institute's assumption that 5.5 to 6.0 percent is enough for all aggregates.

The studies reported by Galloway and Epps were conducted at the Texas Transportation Institute (TTI) and resulted in yet another gradation and range of asphalt contents (15). This gradation is quite similar to the two reported above, but the range of asphalt content was 5 to 7 percent, with the design percentage established by tests of the type recommended by FHWA. Other information of interest gleaned from this reference follows:

1. It was found that relatively dry aggregates should be used to avoid vapor release after the aggregate is coated.
2. Problems of crusting on the surface of the load during haul were experienced and use of insulated covers over the load to avoid heat loss was recommended.
3. It was noted that most types of compaction equipment have been used successfully, but that medium to light weight vibratory rollers are probably better than heavier rollers.
4. The vibrating screed on laydown equipment is probably better for this porous asphalt application than a tamping screed.
5. Freeze-thaw testing at TTI also indicated that damage from this environmental factor is minimal.

The literature review described in some detail above was very useful as a means of eliminating many of the uncertainties existing in construction of a type of pavement system outside the direct experience of pavement engineers in the Austin area.

The selected mix specification consisted of the recommended gradation identified above with 5.5 to 6.0 percent asphalt content subject to drainage test results. In order to obtain this close limit on asphalt content, 5.75 percent was specified with a tolerance of 0.25 percent on asphalt content. The usual tolerance in Texas is 0.5 percent, so it was not certain that this close tolerance could be obtained; however, it was believed that it would be more nearly approached if this tight tolerance was exercised in the specifications. The surface thickness of 2.5 inches (6.3 cm) recommended by Thelen and Howe was also selected for this project (3).

The literature offered some insight as to requirements on compaction of the components of the porous asphalt pavement, but the specificity available from the established stability mix design and construction procedures is missing (3, 15). It was decided that compaction with light equipment should be applied on a closely observed basis to avoid over-compaction and collapsing of pores during construction.

RESERVOIR BASE COURSE DESIGN

Structural Design

In the proposed porous pavement facility, the base consists of large-sized and graded stones, lightly rolled into an open, interlocking structure which not only transmits mechanical loads, but also stores stormwater runoff. This water is held in the reservoir formed by voids in the rock matrix until it can percolate into the soil, or otherwise drain from the site. The choice of base thickness is dictated by hydrological considerations for runoff storage, rather than on ability to spread a wheel load to reduce subgrade stresses as for conventional pavements except on steep slopes where minimum pavement depths are determined by load requirements.

The lot constructed at Austin had a subgrade of limestone and dense soils weathered from the limestone. There was really no need for a substantial base course to reduce pressures on the subgrade, so any reasonable thickness dictated for stormwater storage would have been adequate.

The gradation limits recommended by Thelen and Howe were adopted because they represented the state of the art for porous pavement base courses (3). The stone base course was specified to have a minimum particle size of 1.5 inches (3.8 cm) and a maximum size of 2.5 inches (6.3 cm). A gravel top course two inches in thickness was specified to have a minimum size of 3/8-inch (0.9 cm) and a maximum size of 5/8-inch (1.6 cm).

Compaction or rolling of the stone base course and the gravel top course was specifically precluded by the specifications. Previous experience indicated that the density and mechanical interlock of the stones placed without compaction was sufficient to carry wheel loadings without unacceptable deflections or permanent deformation.

Stormwater Detention Design

The total thickness of the reservoir base course for porous pavement systems can be determined from a dynamic mass balance of inflow to and outflow from the porous pavement system. Manual calculations and a computer model were developed after the porous pavement facility was constructed and are described in Section 7.

In the design of the Austin porous asphalt parking lot, a 5.2-inch (13.2 cm) storm which approximates a 25-year 3-hour storm, was selected for design of the base reservoir. Assuming 40 percent voids, the water storage requirements for the stone base course dictated a 13-inch (33 cm) thickness. However, the Austin site is sloped (1.5 percent) and Thelen and Howe indicate that the stone base course should be much thicker on the downslope end for applications on sloping ground (3). Therefore, in the design of the Austin lot the downslope end was made thicker and the upper end made no thicker than necessary to handle the mechanical loads. This dictated a thickness of 24 to 30 inches (61 to 76 cm) on the northwest (downslope) corner to provide a nearly level pavement surface.

CONSTRUCTION DETAILS

Specifications

Thelen and Howe offered a very limited but informative set of specifications for the construction of a porous asphalt pavement (3). Galloway and Epps offered a much more detailed set of specifications for an open-graded friction course (15). Features of both of these specifications have been combined into the format of City of Austin Specifications to arrive at a tentative set of specifications that were used on this project (16). The porous asphalt pavement specifications used appear in Appendix A.

Site Preparation

At the porous asphalt lot site, the existing temporary parking lot consisting of compacted road base was simply bladed away, exposing a subgrade of exposed and partially exposed limestone that was essentially impervious (Fig. 17).

Base Course Preparation

The stone base course was obtained and placed by the City of Austin Department of Public Works. The partially completed base course placed by the City of Austin was inspected on February 20, 1981. It was noticed that the base material did appear to be open-graded and more or less uniform (Figs. 18-20), but that some of the material had a coating of fines it that would, of course, reduce the final void space. The specification for the stone base course called for material that would pass a 2.5 inch (6.3 cm) sieve and all be retained on a 1.5 inch (3.8 cm) sieve. This material appeared to approximate the specification, except for some material that would not pass a 2.5 inch (6.3 cm) sieve and the fines that would pass a 1.5 inch (3.8 cm) sieve. There was no requirement for compaction of the stone base course, and it appeared that it was being laid down essentially as specified, except for the mixing of the fines at some locations. It was also noticed that the grader had apparently introduced some fines that choked up small areas, approximately five percent of the surface area, of the base material.

Asphalt Mix

The substantial differences between the desired porous asphalt mix and conventional dense-graded asphalt concrete mixes required some coordination to ensure adequacy of the product. Most of these questions arose after the specifications were presented to the testing laboratory preparing the mix requirements for the asphalt plant. Some of these questions and their practical resolutions are discussed below.

The aggregate supplier found that a "Type D" aggregate commonly used in highway construction for a fine graded surface course approximated the grading specified. Review of this gradation indicated that it required 15 to 20 percent less coarse material retained on the No. 4 sieve and would allow around 10 percent more fine aggregate passing the No. 8 sieve. (Differences in sieve sizes specified precluded an exact comparison.) It was decided that this aggregate was the closest gradation available without high costs for special aggregate products, and that it would provide the void space required for porosity.

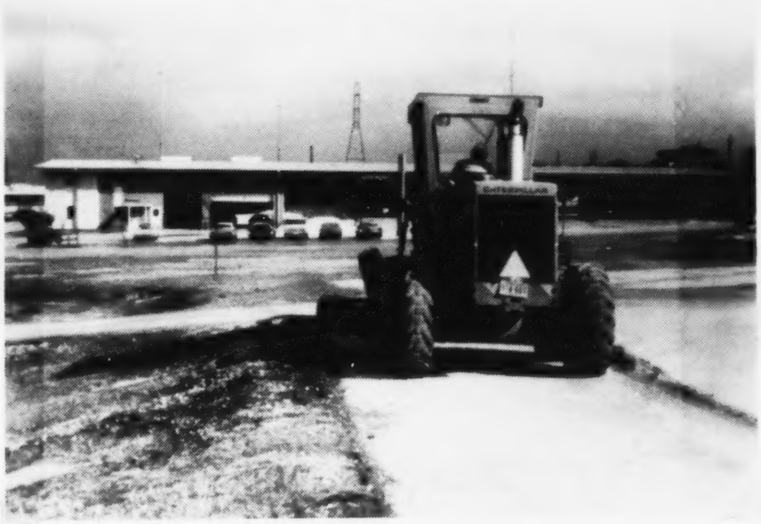


Fig. 17. Porous asphalt parking lot site preparation.

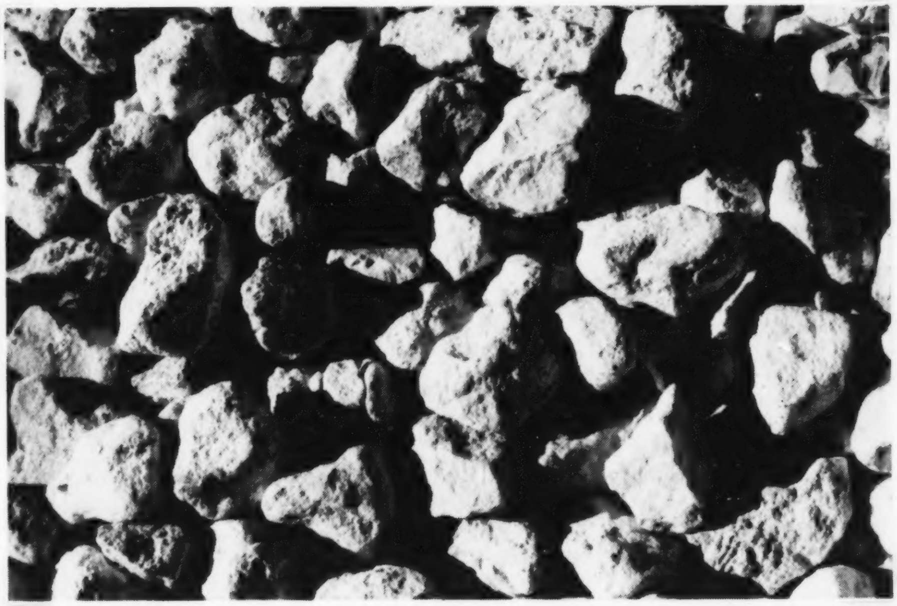


Fig. 18. Reservoir base course. Note the uniformity of stone size.

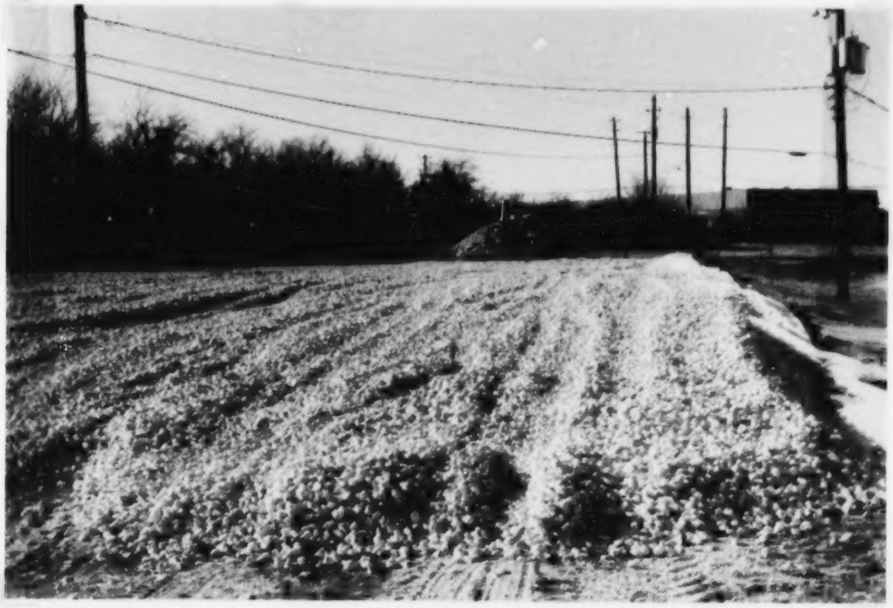


Fig. 19. Reservoir base course placement.

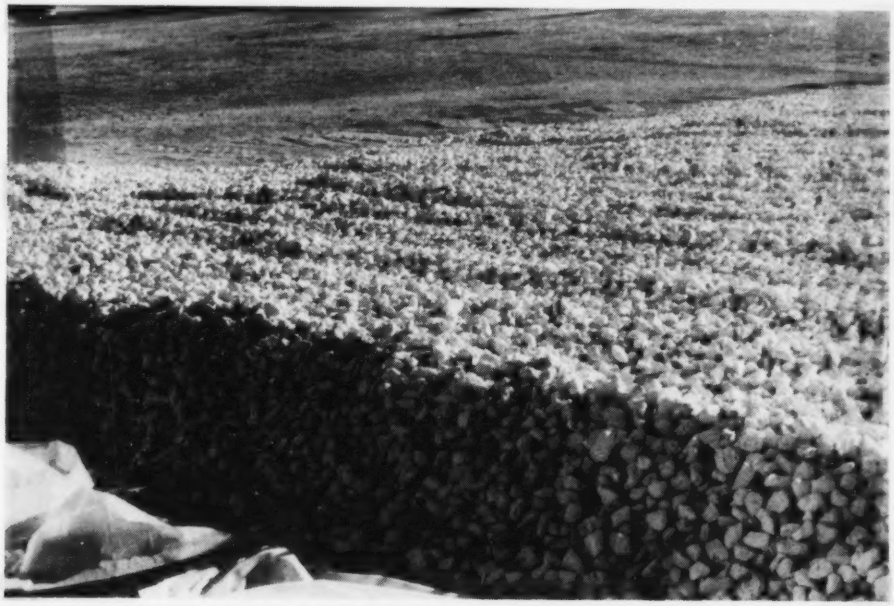


Fig. 20. Cross-section view - reservoir base course.

AC-10 asphalt cement is commonly used in hot mixes in the Austin area, and the supplier preferred to use it. AC-20 asphalt cement had been recommended by Thelen and Howe for use of asphalt cement with a penetration at 77 F (25 C) of 50 to 60 in southern areas to reduce scuffing at the surface caused by wheels turning (3). As the penetration of an asphalt cement is a function of its penetration index as well as its viscosity grade, the penetration at 77 F (25 C) of 50 to 60 was defined as the criteria. However, the AC-10 products used in this area were known to have penetrations in the order of 85 to 100, so the AC-20 was finally selected for use in the porous asphalt mix.

There was considerable confusion over the concept that the mix was not to be optimized on the basis of maximum density as for conventional dense-graded mixes. It was explained that around 16 percent voids was desired for purposes of permeability, and that the percent of asphalt desired was that necessary to provide a good coating on the aggregates without draining or dripping. The laboratory was advised to use 5.5 percent asphalt content, compact the materials using the 50-blow Marshall Procedure, and to test to see what stability and flow resulted. This resulted in a mean stability of 645 pounds (293 kg) and a flow of 19.

Further discussion was conducted because the literature had mentioned a measured stability of 1400 pounds (636 kg) and a flow of 9 (16). This was resolved by noting that a minimum stability of 500 pounds (227 kg) and a range of flow from 8 to 15 had been established by Thelen et al. as mix design criteria (13). Very little could actually have been done to effectively increase the stability or reduce the flow without loss of the desired porosity.

It was noted that the rock dust available in the aggregate selected only resulted in 0.4 percent passing the No. 200 sieve instead of the 2 to 5 percent specified. As previous specifications did not require any material to pass the No. 200 sieve and the resultant mixes had performed well, this was accepted. The purpose for requiring the minimum of 2 percent passing the No. 200 sieve had been to provide additional viscosity for the binder. It was believed that the use of the AC-20 asphalt cement would provide sufficient viscosity.

The question of a suitable level of density arose, primarily because of its use as primary acceptance criteria for conventional mixes and its relationship to stability. Review of the literature produced only one report of density, and that was at 126 pcf (2019.8 kg/m^3). This appeared to be a reasonable value with a minimum of 16 percent voids.

Transporting

The weather was mild on the morning of May 7, 1981 when the mixture was delivered and the beds of the conventional dump trucks used to carry the mixture were covered with tarpaulins to retain heat.

Placement

The porous asphalt surface course was placed on the morning of May 7, 1981. This placement was observed by representatives of the City of Austin; Espey, Huston & Associates, Inc.; Mr. John English, EPA Project Manager; a representative of the testing laboratory that prepared the mix; and Dr. J. Brent Rauhut of Brent Rauhut

Engineering, Inc. Dr. Rauhut maintained a record of proceedings and his impressions through dictation on a small dictaphone. Most of the comments below were transcribed from this dictation.

Although the specifications called for no compaction of the stone topping, it was compacted lightly to gain the finish desired. It appeared to have been placed very well with only a tiny bit of crushing of particles resulting from the compaction (Fig. 21).

Discussion with the foreman for the City of Austin laydown crew indicated that the laydown machine did not have a vibrating screed and thus did not meet the specifications, but it was all that they had. However, he had brought a special spray that decreased the tendency to sticking somewhat without retarding the asphalt. An 8-ton (7.3-metric ton) pneumatic roller was available for use in compaction.

The specifications required that the temperature of the porous asphalt mixture be between 180 and 260 F (82.2 and 126.7 C) when placed. There was concern that there would be trouble in laying it at temperatures approaching 180 F (82.2 C). This appeared to be a valid concern and it was agreed to lay the material around 240 to 260 F (115.6 to 126.7 C). The first pass was placed along the west side of the parking lot at a temperature of 285 F (140.5 C), which was hotter than intended. It went down very easily (Fig. 22). The first pass of the 8-ton (7.3-metric ton) pneumatic roller was made shortly after laydown and it caused very heavy rutting (Fig. 23). It was noted that the roller had become sticky and was picking up topping rock and delivering it on to the paved area. It was decided to let the material cool down to around 180 F (82.2 C) before further compaction. The compaction was then completed with six passess of the 8-ton (7.3-metric ton) pneumatic roller after the mix had cooled. It appeared to be quite dense and to have less voids than desired (Fig. 24 and 25). A simple test was conducted by pouring water on top of this first pass. Although it appeared to be quite dense, the water did drain through it rather steadily.

There was considerable discussion about how the rolling should be conducted in view of the problem that had been encountered. It was decided that compaction would be deferred until the mix had cooled down toward 180 F (82.2 C). Also, it was decided that the 8-ton (7.3-metric ton) pneumatic roller was too heavy for what we were doing, and that a small one-ton vibratory flat-wheel roller should be expedited to the site for initial break-down rolling before the pneumatic roller was used.

It was also noted that the total thickness of the porous asphalt surface course was only 1.5 to 1.75 inches (3.8 to 4.4 cm) in lieu of the 2.5 inches (6.3 cm) specified. This was not considered to be a problem as the stone topping appeared to be quite stable and little additional spreading of the load could be expected from an additional inch (2.5 cm) of the porous asphalt. Also, the thinner surface should be less prone to rutting and should pass water easier.

The second strip of pavement was compacted by four passes of the 8-ton (7.3-metric ton) pneumatic roller after it had been in place around two hours and was at a temperature estimated at about 150 to 160 F (65.5 to 71.1 C). This appeared to produce an acceptable porous asphalt surface within the guidelines for this project. Consequently, the third strip from the west was compacted in the same manner and with the same number of passes (Fig. 26).

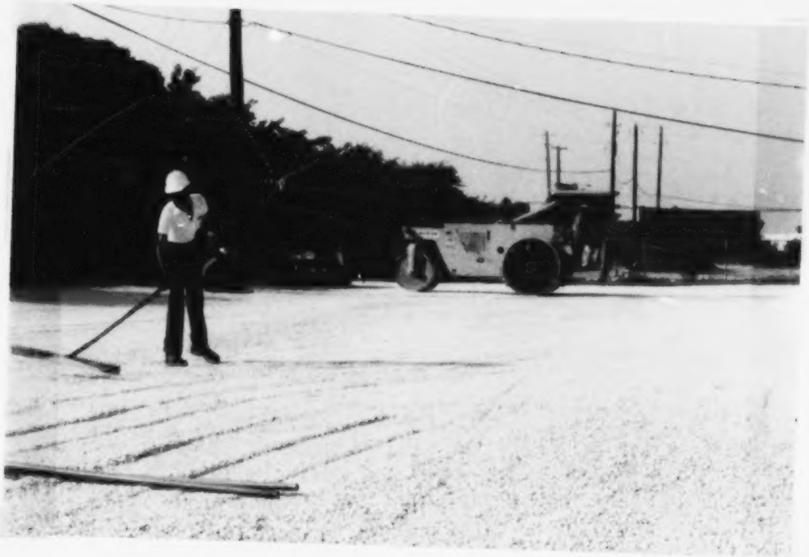


Fig. 21. Reservoir base course - finished grade.

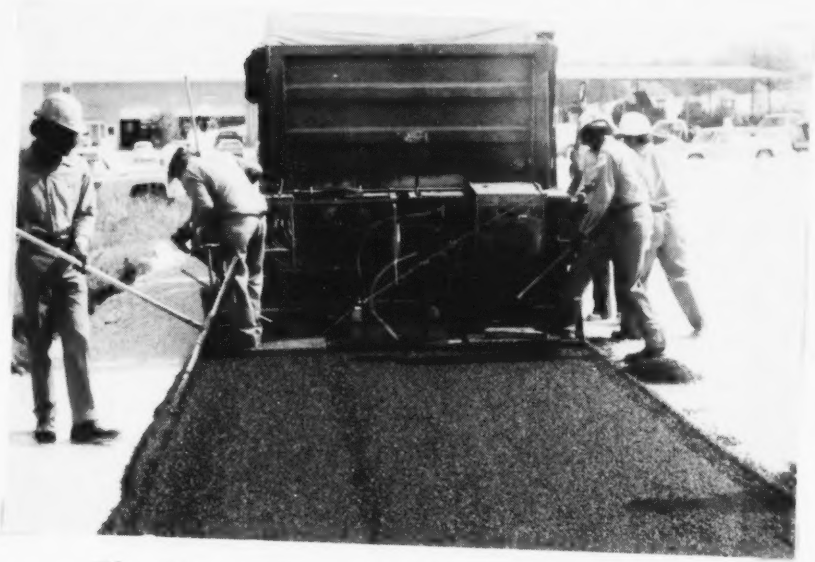


Fig. 22. Porous asphalt top course placement.

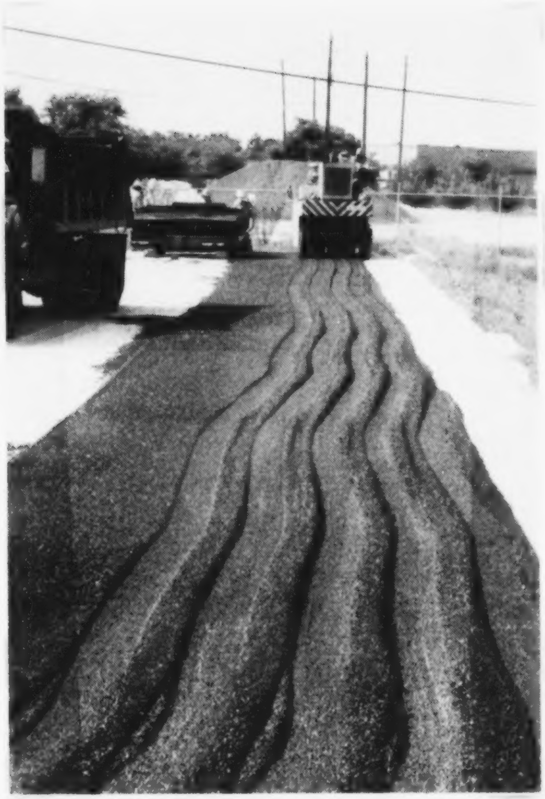


Fig. 23. First pass compaction by the 8-ton (7.3-metric ton) pneumatic roller. Note heavy rutting.

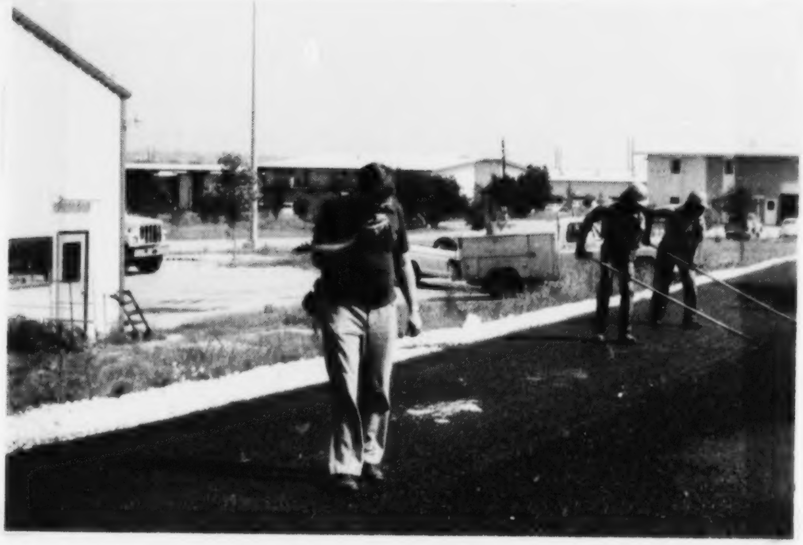


Fig. 24. Porous asphalt top course completed compaction.

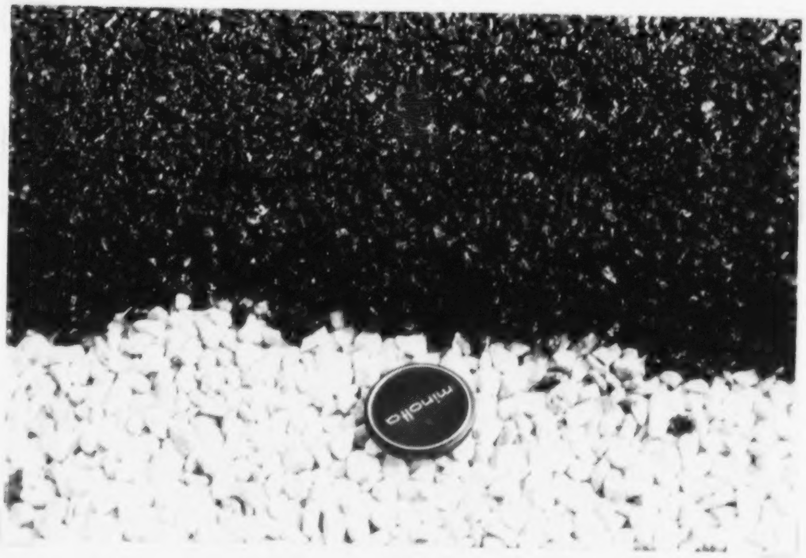


Fig. 25. Comparison of porous asphalt top course and 1/2" diameter reservoir filter course.

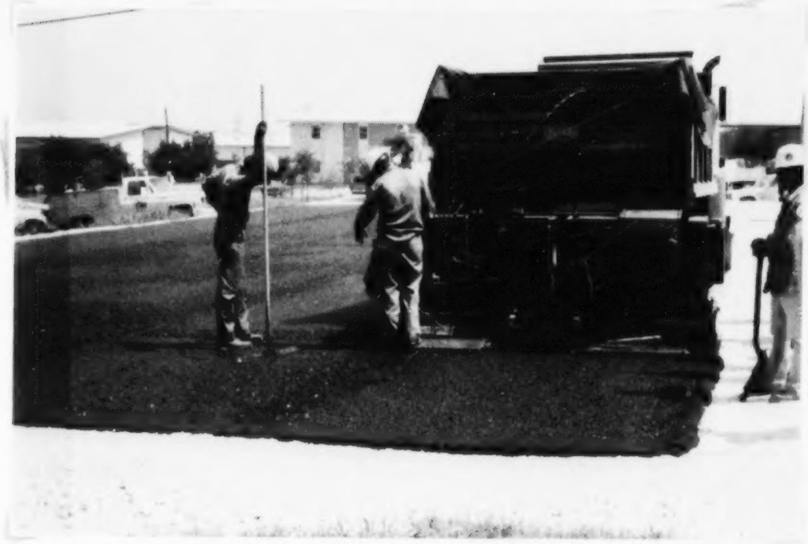


Fig. 26. Placement of the third strip.

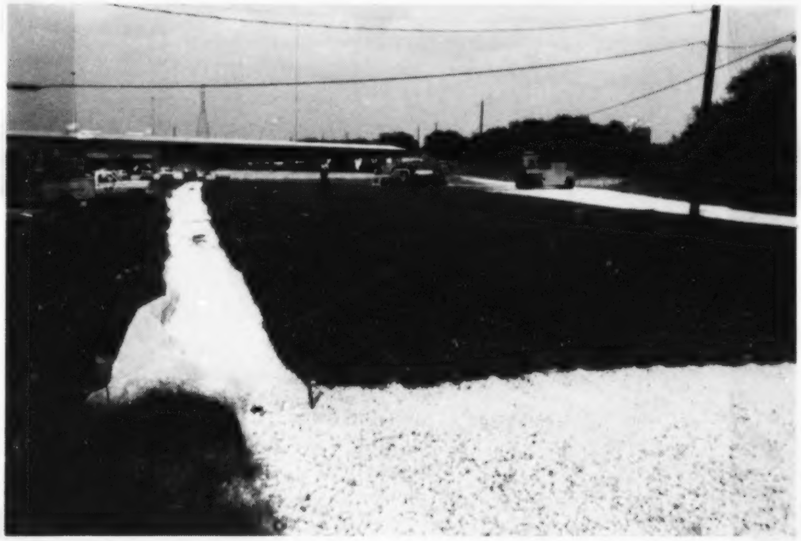


Fig. 27. Finished porous asphalt lot.

As an experiment, only the one-ton (0.9-metric ton) tandem flat-wheel roller was used for a single pass for the 4th, 5th, and 6th strips of the parking lot. This roller was operated as a one-ton (0.9-metric ton) static roller without the two-ton (1.8-metric ton) vibratory capability operating. This roller operated very slowly, so it spent a considerable amount of time at any one location. The compaction for this portion of the surface appeared to be reasonably acceptable also.

For the closure strip on the north end of the lot (transverse to the other strips), the small flat wheel tandem roller was run first and then followed with the heavier pneumatic roller. This resulted in a somewhat more stable and denser surface, but tests by simply pouring water on the surface indicated that it was draining very well also.

As the laydown crew was running out of mix, it was decided to halt the placement after six strips approximately sixty feet (18.3 m) in total width were placed. This left only a triangular space of zero width at the south end and approximately 30 ft (9.1 m) of width on the north end unpaved along the east side. It was agreed that runoff from this area could be channeled away from the experiment, and that the experiment would not be greatly affected.

Experimentation indicated that the type of compaction was probably less important than letting the surface cool down after placement to a temperature near 180 F (82.2 C). At the lower temperatures, several widely disparate types of compaction were applied with reasonable success.

On the basis of observation alone, the porous asphalt surface appeared to be reasonably stable and to satisfy the requirements for permeability necessary for this project (Fig. 27).

GUIDELINES FOR FUTURE DESIGN AND CONSTRUCTION

The construction of a single porous pavement facility was far too limited to develop general guidelines for future application at high confidence levels. However, tentative recommendations are provided below on the basis of the limited experience to be gained from a single small project.

It was apparent from this project that conventional mixture temperatures near 260 to 280 F (126.7 to 137.8 C) should be used for laydown, but that compaction should be delayed for this type of mixture until it had cooled down near 180 F (82.2 C). If this approach is followed, the material placement should be easily effected and a stable surface produced with the desired porosity.

The apparent success in densifying the surface course using six passes of the 8-ton (7.3-metric ton) pneumatic roller, four passes of the 8-ton (7.3-metric ton) pneumatic roller, one pass of the 1-ton (0.9-metric ton) pneumatic roller, and a combination of first pass with the 1-ton (0.9-metric ton) flat-wheel tandem roller followed by the heavier pneumatic roller indicates that light compaction equipment is preferable, but that a reasonable surface can be attained in a variety of ways as long as the mixture is not too hot when compacted.

It is believed that the gradations for the stone base, the stone topping course, and the porous asphalt that have been developed in the past and used on this project with some modifications are quite adequate. However, the placement and compaction of the porous asphalt merits considerable experimentation before large-scale use of porous asphalt pavements.

As the porous asphalt mixtures and the stone base placement is very different from hot mixes and base courses for conventional roadway construction, it is extremely important that the preconstruction process be well coordinated. This can avoid serious misunderstandings, loss of time, and possible failures in production of the facility desired.

EXTRACTION, STABILITY, AND INDIRECT TENSILE STRENGTH TESTING RESULTS

An extraction test was conducted on the mix collected at the plant. The resulting gradation is compared to that specified below:

Sieve Sizes	Percent Passing	
	Specified	Measured
1/2" (1.3 cm)	100	100
3/8" (0.9 cm)	90-100	93.6
#4	35-50	36.4
#8	15-32	15.6
#16	2-15	11.1
#200	2-5	4.7
Percent Asphalt	5.5 to 6.0	5.8

Perhaps the best indication of the strength attained by the porous asphalt is obtained by removing cores and testing them in indirect or diametral tension. Six cores approximately four inches (10.2 cm) in diameter were removed on the porous asphalt parking lot from the locations indicated in Figure 28. Two cores were each tested at temperatures of 40, 70 and 100 F (4.4, 21.1 and 37.8 C). After indirect tensile strength testing had been completed, the density of each core was measured using the procedures in ASTM D-1188 (14). The approximate thickness of the porous asphalt cores were also measured and the total testing results appear in Table 4.

The approximate thicknesses of the porous asphalt cores ranged from 1.5 to 2.5 inches (3.8 to 6.3 cm), with a mean thickness of 2.0 inches (5.1 cm). These measurements are necessarily approximate as the top and bottom surfaces of the porous asphalt cores were quite uneven. The measured densities for this material ranged from 124 to 132 pcf (1987.9 to 2116.1 kg/m^3), with a mean of 129 pcf (2068 kg/m^3). This appears to represent a relatively well-compacted mixture considering the rather high percent of voids sought and obtained in this porous asphalt.

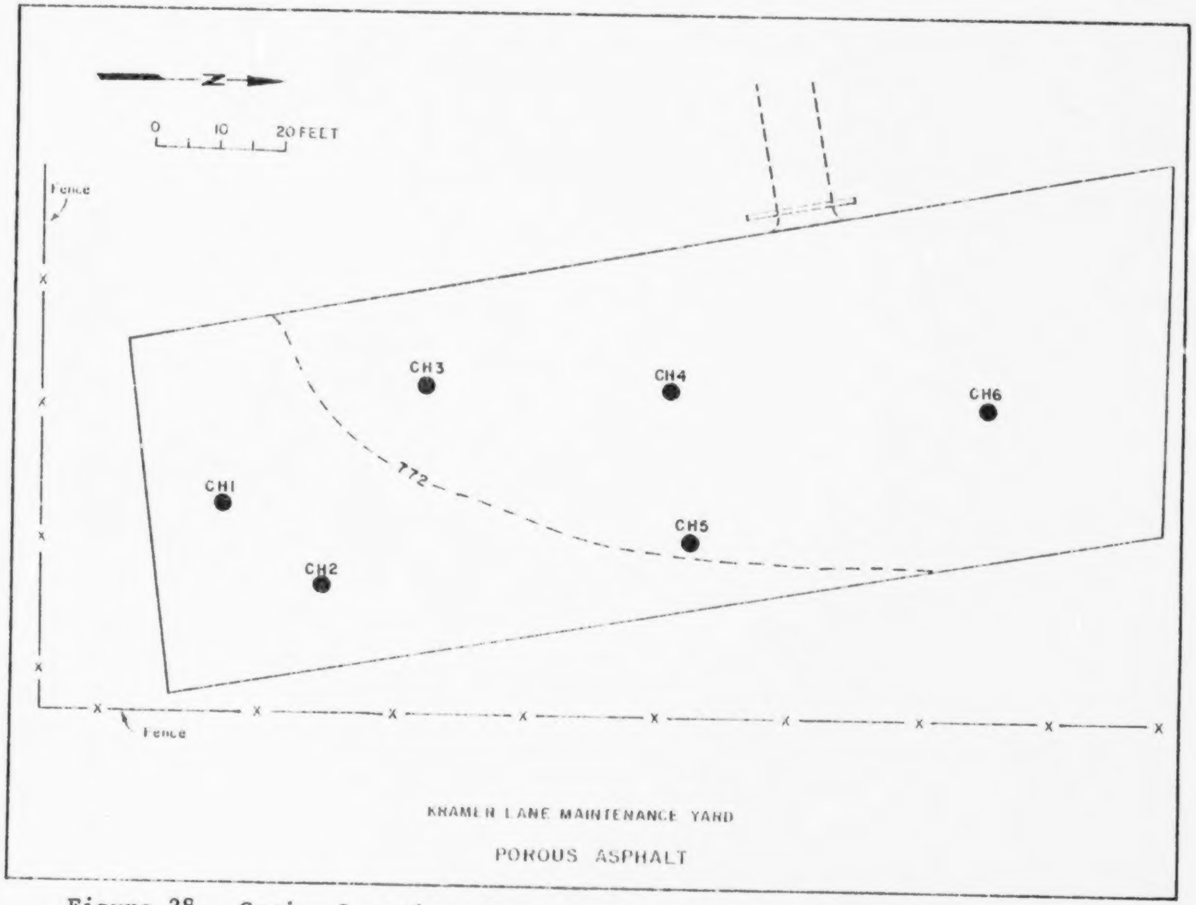


Figure 28. Coring Locations for Porous Asphalt Cores.

TABLE 4

INDIRECT TENSILE AND DENSITY TEST RESULTS FOR POROUS ASPHALT SURFACE, KRAMER SERVICE CENTER, AUSTIN, TEXAS

Core No.	Thickness (Inches)	Density (PCF)	Test Temperature ($^{\circ}$F)	Indirect Tensile Strength (PSI)
1	2.2	127	70	81
2	1.8	129	40	161
3	2.1	124	70	71
4	1.8	130	100	79
5	2.5	130	100	63
6	1.5	132	40	210
Mean Values	2.0	129		

1 inch = 2.54 cm
1 PCF = 16.07 kg/m^{3}
$^{\circ}$F = 5/9 $^{\circ}$C +32
1 PSI = 703 kg/m^{2}

The results of the indirect tensile test are presented in Fig. 29, where indirect tensile strengths are plotted versus test temperatures. Strengths for asphalt concrete mixes are considerably affected by the temperature of the mix in place. The porous asphalt mix varied in strength from an average of 185 psi (13 kg/cm^2) at 40 F (4.4 C) to an average of 70 psi (4.9 kg/cm^2) at 100 F (37.8 C). For comparison, a similar set of data for fourteen hot mix asphalt concrete (HMAC) cores from eight pavements in Texas are plotted on Fig. 29. Also, mean values for 400 asphalt stabilized base cores and five hot mix asphalt concrete surface cores tested at 75 F (23.9 C) by the Center for Highway Research, University of Texas at Austin, are plotted.

As expected, the indirect tensile strengths of the porous asphalt cores are lower than those of typical dense-graded HMAC cores. The strengths at lower temperatures are still relatively high, however, and those at the most critical higher temperatures did not vary greatly from those for dense-graded mixes. The greatest relative difference between the porous asphalt and dense-graded mixes appears to occur in the middle range of temperatures represented by 70 F (21.1 C). The indirect tensile strengths for the porous asphalt cores did not vary greatly between 70 and 100 F (21.1 and 37.8 C), so that the minimum tensile strength within this range of temperatures was on the order of 60 psi (4.2 kg/cm^2) or greater. This does not compare too poorly with the 85 psi (6.0 kg/cm^2) average at 100 F (37.8 C) for the HMAC cores. The strength of the porous asphalt was greater than anticipated as compared to dense-graded mixes, and it may be expected to be reasonably stable.

IN SITU PERMEABILITY RESULTS

The permeability characteristics of the porous asphalt surface was determined by in situ tests conducted on December 14, 1982 using an infiltrometer designed and fabricated specifically for this study. The infiltrometer consists of a 6-inch (15.2-cm) inside diameter clear PVC pipe 18 inches (45.7 cm) high with a stopper mechanism which allows a timed release of a known volume of water through a 3.5 inch (8.9 cm) diameter hole at the base of the infiltrometer (see Fig. 30). Table 5 presents the results of the infiltrometer test at the locations referenced on Fig. 31.

The permeabilities of the porous asphalt surface ranged from 152 in/hr (386 cm/hr) to 5290 in/hr (13,437 cm/hr) with an average rate of 1766 in/hr (4486 cm/hr). This rate compares to an average rate of 70,000 in/hr (177,800 cm/hr) for the 2-inch (5-cm) reservoir base course (2). Notable exceptions to this average rate occurred on the west side of the lot (test locations 1, 7, 13, 19, 22 and 25), throughout the driveway path (test locations 13, 14, 15, and 16) and in the northeast corner (locations 21, 24, 26, and 27). Lower than average infiltration rates on the west side of the lot can be attributed to rolling the asphalt at a temperature higher than 180 F (82.2 C), as discussed in the previous section. The driveway path has more traffic than other parts of the lot and may be compacted more than normal. The extreme south end (test locations 2, 3, 4, 5 and 6) has had essentially no traffic. The northeast corner of the lot was noted to have soil accumulating in the pores of the porous asphalt surface, possibly transported there by tires of vehicles.

VISUAL INSPECTION AFTER VEHICLE USE

The porous asphalt parking lot was inspected at the time of the permeability results after eighteen months of use. The surface appeared to be in excellent

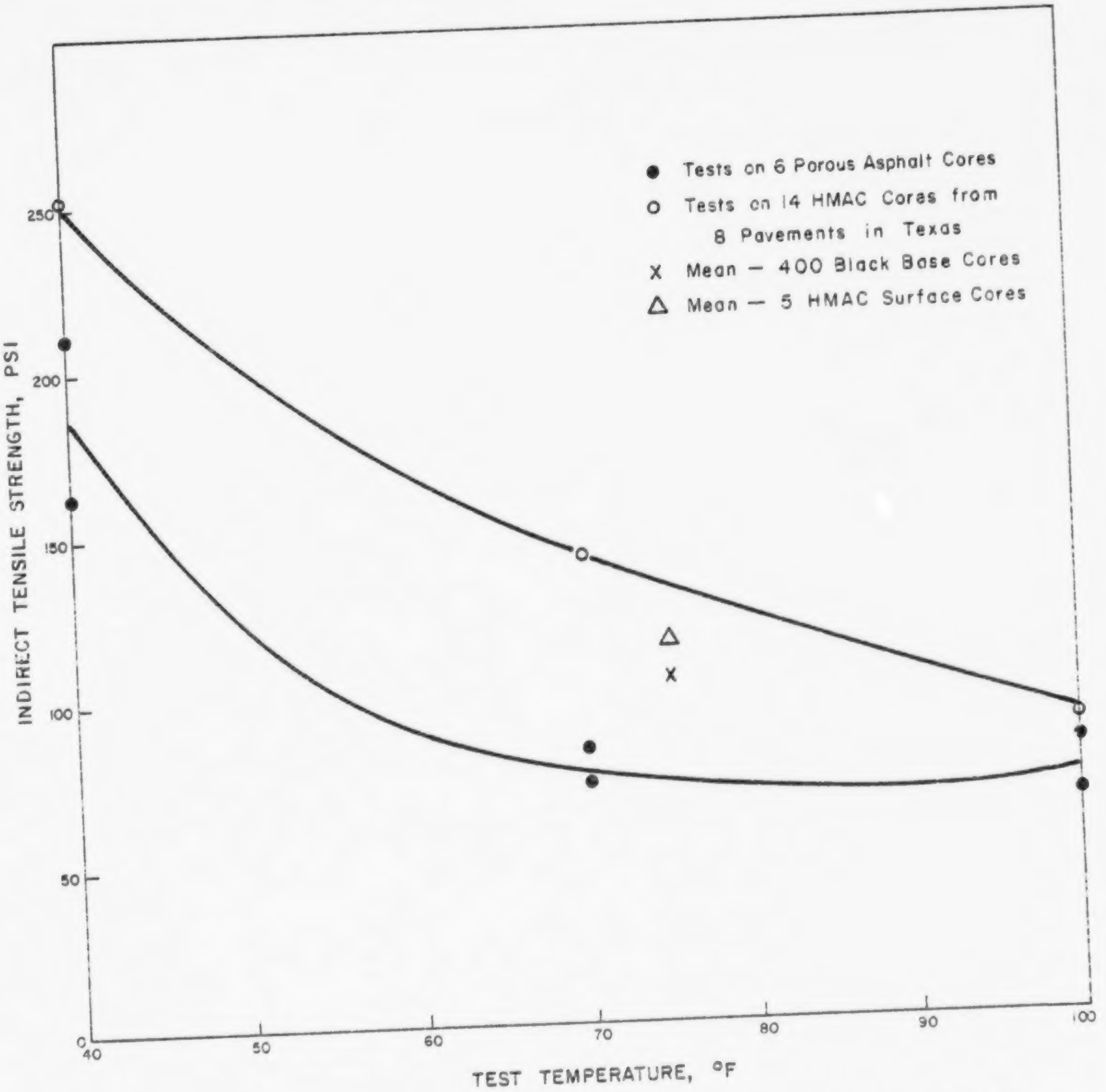


Figure 29. Comparisons of Indirect Tensile Test Results for Porous Asphalt Cores from Kramer Service Center to Typical Dense-Graded HMAC Cores.

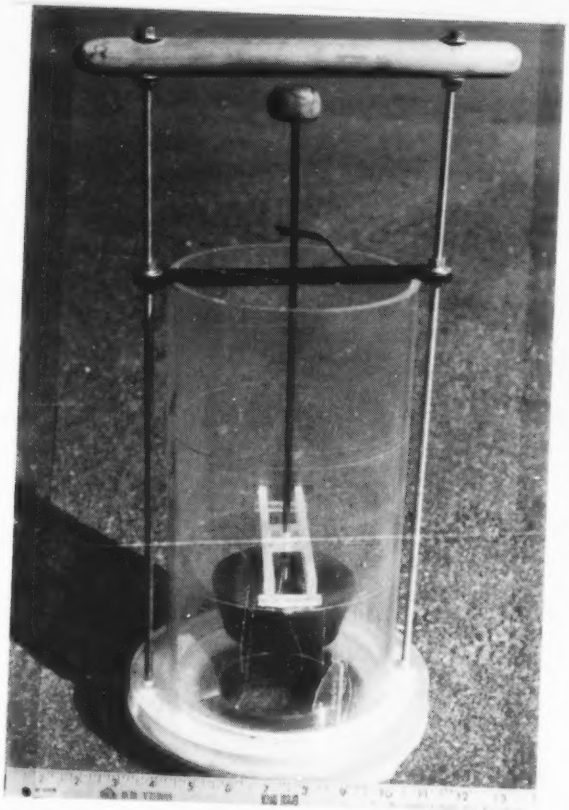


Fig. 30. Infiltrometer used for permeability measurements.

TABLE 5

IN SITU PERMEABILITY TEST RESULTS
POROUS ASPHALT LOT - KRAMER LANE SERVICE CENTER

Location[1/]	Time to Drain (sec)	Infiltration Rate (in/hr)	Infiltration Rate (cm/hr)
1	142	298	757
2	12	3,527	8,959
3	9	4,702	11,943
4	20	2,116	5,375
5	10	4,232	10,749
6	9	4,702	11,943
7	123	344	874
8	10	4,232	10,749
9	8	5,290	13,437
10	15	2,821	7,165
11	13	3,255	8,268
12	24	1,763	4,478
13	279	152	386
14	105	403	1,024
15	53	798	2,027
16	72	588	1,493
17	47	900	2,286
18	35	1,209	3,071
19	62	683	1,735
20	49	864	2,195
21	150	282	716
22	52	814	2,067

TABLE 5 (Concluded)

Location[1]	Time to Drain (sec)	Infiltration Rate (in/hr)	Infiltration Rate (cm/hr)
23	13	3,255	8,268
24	67	632	1,605
25	34	1,245	3,162
26	104	407	1,034
27	239	177	449

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[1] Refers to Fig. 31.

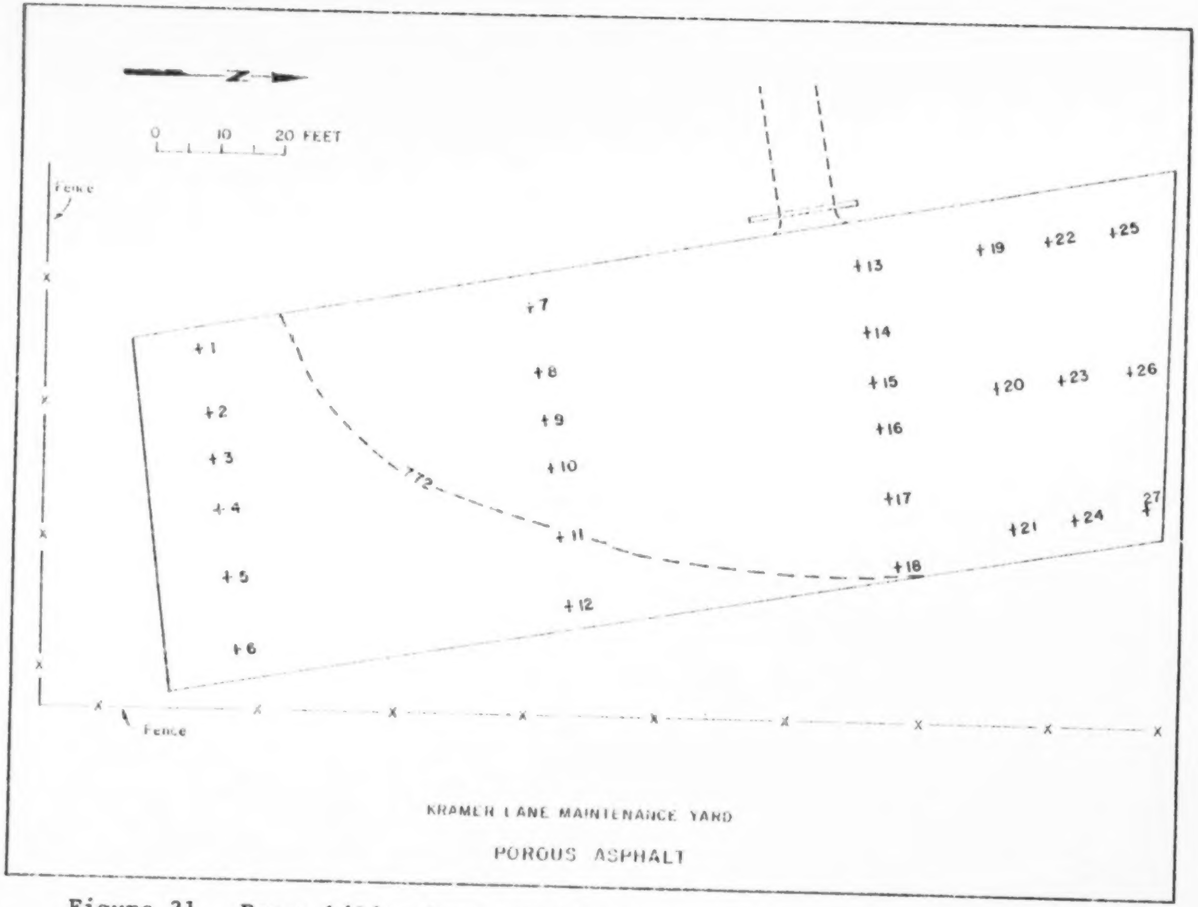


Figure 31. Permeability Test Locations.

condition. There was no noticeable rutting, cracking, or scuffing. There were a few small loose gravel particles on the north end of the lot, but it is believed that most of these were present when the surface was completed rather than subsequently raveled from the surface.

There appeared to be some soil accumulating in pores on the north side of the lot. This soil was apparently transported onto the pavement by tires or wind, and should be removed by vacuum to avoid choking the pores.

CONSTRUCTION COSTS

The following cost data was formulated based on construction bid prices and cost estimates for conventional hot mix asphalt parking lot construction in the Austin area:

COST FOR CONVENTIONAL HOT MIX ASPHALT CONSTRUCTION

Item	Cost[1] ($/sq yd)
Subgrade Preparation	1.00
Base Material	3.50
Hot Mix Asphalt	3.75
Concrete Curb	0.25
Subtotal	8.50
Engineering and Testing (+17%)	1.50
Total	10.00

[1] $1/yd^2 = \$1.2/m^2$

The porous asphalt construction costs, tabulated below, are the actual costs incurred by the City of Austin for construction of the 1,711-square yard (1431-square meter) parking lot at the City's Public Works Kramer Lane Service Center described in this section.

COST FOR POROUS HOT MIX
ASPHALT CONSTRUCTION

Item	Quantity	Cost ($)
Base Material	75 tons[1]	270
2-Inch Rock	800 tons	3,955
½-Inch Rock	150 tons	595
Hot Mix Asphalt	189 tons	3,776
24-Inch Pipe Culvert	20 L.F.[2]	175
Vehicle and Fuel Charges	--	1,623
Salaries and Fringe Benefits	--	2,107
Indirect Costs	--	614
Survey	--	1,320
Engineering and Testing	--	2,644
Total		17,079

[1] 1.1 ton = 1 metric ton.

[2] L.F. = linear feet = 0.0348 meter

The per square yard cost is arrived at by dividing the total cost ($17,079) by the area paved (1,711 square yards, 1,431 square meters), or $10 per square yard ($12 per square meter).

SECTION 6

RESULTS

RESULTS OF THE MONITORING SURVEYS

The hydrologic and water quality results obtained during the stormwater surveys are discussed below with respect to hydraulic performance and intra-event pollutant characteristics. Along with inflow and discharge characteristics, the ratio of observed runoff to observed inflow was calculated for each event. Theoretically, this ratio should always be less than unity constrained by mass continuity. However, when measurement error is introduced in either the runoff or inflow records, a value greater than one can result. In fact, allowing a 10 percent error for each measurement, i.e., 10 percent less observed rainfall concurrent with 10 percent more observed discharge, a ratio of 1.22 results. Subsurface runoff at the porous asphalt and gravel trench lots was monitored until flow ceased. These lots were open systems and did not prevent discharge, but rather, detained the discharge. Hence the runoff ratios cannot be used as an indicator of system storage performance. The gravel trench was lined with an impermeable liner and the porous asphalt lot was constructed on relatively impervious limestone; hence the only storage of inflow would occur in surface wetting of the pavement and base course material. The detention time was calculated as the difference in time between the center of mass of the inflow and the center of mass of the discharge hydrograph. A summary of hydraulic characteristics of the pavements during each runoff event is presented in Table 6.

Several studies have accumulated water quality information observed during urban stormwater events. Three classes of intra-event stormwater quality trends are frequently observed:

1. Initial high concentrations often occur at the beginning of the storm event, reflecting the initial removal of contaminants from the catchment. This phenomenon is termed "first flush".
2. Variations in constituent concentrations may parallel the rising and descending flow levels of the storm hydrograph.
3. The absence of a well-defined intra-event trend in constituent levels may be observed.

A general water quality comparison between pervious and impervious lots, presenting flow-weighted average concentrations of total suspended solids (TSS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total nitrogen (TN), total lead (Pb) and total zinc (Zn) is discussed later in the section. The complete set of field and laboratory results are presented in tabular and graphical form in Appendix C.

TABLE 6

HYDRAULIC SUMMARY OF STORMWATER SURVEYS

Pavement Type	Event Date	No. of Sprinklers[1]	Total Inflow (in)	Duration (min)	Average Intensity (in/hr)	Peak Discharge (cfs)	Time to Peak (min)	Total Discharge (in)	Runoff Ratio[2] (in/in)	Detention Time (min)	7-day Antecedent Rainfall[3]
Porous Asphalt[4]	03/22/82	8	0.94	60	0.94	0.269	58	0.58	0.73	42	0.02
	04/05/82	9	0.50	62	0.48	0.253	54	0.64	1.28	42	0.09
	06/01/82	8	1.53	55	1.67	0.237	53	0.56	0.37	42	0.00
Lattice Block Lot	03/02/82	4	1.06	75	0.85	0.034	55	0.19	0.18	11	4.03
	03/11/82	6	1.08	60	1.08	0.078	40	0.39	0.36	12	0.00
	03/18/82	8	1.08	34	1.90	0.113	24	0.25	0.23	11	0.03
Gravel Trench	03/03/82	3	0.64	94	0.41	0.440	60	0.49	0.76	29	4.03
	03/19/82	4	0.64	70	0.56	0.580	66	0.41	0.64	24	0.03
	04/04/82	4	0.64	59	0.65	1.667	55	0.49	0.77	19	0.12
Asphalt	06/03/81	*	0.34	46	0.44	0.84	53	0.40	1.18	1	2.48
	05/11/82	8	0.21	10	1.26	0.223	7	0.15	0.71	5	0.99
Concrete	03/03/81	*	0.85	120	0.43	0.20	58	0.46	0.55	18	0.53
	06/03/81	*	0.57	33	1.04	0.10	30	0.28	0.48	14	2.48
	10/07/81	*	0.45	90	0.30	0.07	30	0.17	0.38	17	3.71

1 in = 2.54 cm
1 cfs = 28.31 l/s
1 in/hr = 2.54 cm/hr

[1] Values for the gravel trench are the number of water trucks used.

[2] Runoff to rainfall ratio. Subsurface runoff (underflow) measurements are used in the porous asphalt and gravel trench lots. Surface runoff measurements are used for the lattice block, conventional asphalt and conventional concrete lots.

[3] Precipitation amounts recorded at the Austin Airport within the indicated number of preceding days.

[4] Discharge results influenced by infiltration lines along trenches.

*Denotes natural precipitation event. The remainder were sprinkler-induced events.

Pervious Surfaces

Porous Asphalt —

Stormwater runoff conditions were generated at the porous asphalt lot during three sprinkler events. A maximum intensity of 1.67 in/hr (4.2 cm/hr) was achieved with no resulting surface runoff. Hydraulic control problems were encountered at the porous asphalt lot. The lot was constructed above grade, exposing the downslope width and about 25 percent of one side. A 6-mil (0.015-cm) polyethylene liner was placed during construction along the downslope width and exposed length to prevent unregulated lateral discharge. The liner proved inadequate as an impermeable boundary during initial stormwater sampling efforts and an asphalt seal was subsequently applied to the exposed sides. This also was ineffective as a containment measure and channels were subsequently trenched along the exposed width and side. Hydraulic and water quality samples were taken at the V-notch weir located at the intersection of the two trenches. The trenches were to be clay-lined to minimize percolation losses and erosion, however, this mitigative measure was not carried out. Consequently, some base discharge was possibly lost via percolation along the unlined channels, albeit the first and second events recorded high surface runoff ratios (0.73 and 1.28, respectively). The runoff ratio greater than unity probably reflects a measurement error of the rainfall volume.

As presented in Table 6, the total discharge volume, the time to peak flow and the peak discharge rates were similar for each event even though the inflow varied from 0.50 in (1.27 cm) to 1.5 in (3.8 cm) and the nominal intensity varied from 0.5 in/hr (1.27 cm/hr) to 1.67 in/hr (4.24 cm/hr). For each event, the detention time was 42 minutes, indicating a uniform temporal response to the sprinkler inflows. Observed base runoff ranged from 37 to 128 percent of recorded sprinkler inflow. The sprinkler volume records reflect a degree of measurement error possibly accounting for the anomalous runoff ratio greater than unity. The accuracy of inflow measurement is dependent on the density of the rain gage network and the uniformity of the sprinkler spray distribution. During the sprinkler events, the average rain gage density was approximately 1 gage per 2,000 square feet (180 square meters). Similar 7-day antecedent rainfall volumes were recorded for each sprinkler event. Levels of COD, TN and Zn in the underflow during the first and second events indicated a first-flush effect after the stormwater passed through the base layer. Values of TSS during the initial and final storms also reflected an initial rinsing of the pavement surface. The second event had the lowest sprinkler intensity during which time TSS and lead levels paralleled the discharge hydrograph.

Lattice Block Lot —

Three simulated runoff events were monitored at the lattice block facility. A summary of the hydraulic response is presented in Table 6. The number of sprinklers employed and duration of inflow was varied for each event. Observed runoff ranged from 18 to 36 percent of gaged sprinkler volume. The effective storage capacity of the lattice block lot, as estimated by the observed differences between rainfall and runoff, ranged from 0.64 to 0.82 in (1.63 to 2.08 cm).

The detention time of the lattice block lot was uniform for each event, ranging from 11 to 12 minutes. This rapid response time indicates that the runoff which does not percolate into the base layer is transported off the lot within a duration comparable to impervious surfaces. The short detention times at the lattice block lot reflect non-uniform permeabilities of the surface layer. In some areas, the sandy loam is hard-packed and generates surface runoff with a short detention time (characteristic of impervious surfaces). Other areas retain the infiltration characteristics as designed.

Water quality samples were obtained from the surface discharge of the lot, and hence, reflect the water quality of the overland runoff. For the three events, TSS and COD consistently displayed a first-flush effect while TN levels paralleled the discharge hydrograph during two events. Metal concentrations did not display a discernable trend during the initial and final events, while a first-flush response was exhibited by zinc during the second event.

The lattice block construction allowed an initial portion of rainfall volume to be stored in the depressions and sand within the surface interstices before overland runoff began. However, non-uniform surface permeabilities resulted in more surface runoff than expected. In some areas, underlying and adjacent clay soils resulted in a minimal amount of water lost through infiltration and lateral discharge. During a survey conducted after the sampling period the sand level in the interstices was observed to be too high to promote healthy grass productivity, and hence bare sand was exposed over a large portion of the pavement surface. Stormwater suspension of sand particles facilitates their transport during an event to areas of depression. As the sand is compacted, the infiltration capacity decreases and surface runoff increases.

Gravel Trench Lot --

Table 6 presents a summary of the three simulated stormwater events monitored at the gravel trench lot. The City Parks Department 2000-gallon (7571-l) water trucks provided the inflow volumes for each event. Observed subsurface runoff ranged from 64 to 77 percent of recorded volume, with an average of 73 percent for the three events. Observations made during storm events indicated the small diameter surface gravel was impeding the vertical flux of water, i.e., a small portion of surface runoff was flowing across the top of the trench. Estimates of hydraulic detention times ranged from 19 to 29 minutes for the three events.

TSS, COD, Pb, TN and Zn levels paralleled the discharge hydrograph during the first and second surveys. A first-flush effect was observed for each during the third event, which recorded the greatest average inflow intensity, 0.65 in/hr (1.7 cm/hr). The observed high suspended solids concentrations possibly are attributable to scouring of the backfill material supporting an asphalt ramp, constructed across the gravel trench before the initiation of stormwater sampling.

Impervious Surfaces

Conventional Asphalt Lot --

A precipitation event and a sprinkler-generated runoff event were monitored at the conventional asphalt study lot, and the results are summarized in Table 6. The storm event occurred on June 3, 1981 as a result of a squall line spawned by an approaching cold front. A total of 0.34 in (0.86 cm) of precipitation fell during the sampling period, with maximum intensity of 2.32 in/hr (5.9 cm/hr). Approximately 20 percent more surface runoff than precipitation was recorded. This anomaly is possibly attributed to incorrect rainfall measurement, as the gage was located across the street atop a 4-story building. The sprinkler event was created by 8 sprinklers operating for a duration of 10 minutes. A peak discharge of 0.22 cfs (6.23 l/s) was observed, with approximately 71 percent of the recorded inflow appearing as runoff. Low detention times were calculated for each event, indicating a rapid catchment response. The lack of depression storage on the lot, the small surface area and a relatively smooth surface contributed to the rapid response. The disparity between recorded rainfall and discharge for the initial event may have influenced the rapid (1 minute) detention time.

TSS and COD levels exhibited a first-flush effect during the two events. TKN values paralleled the discharge hydrograph during the first and second events. Both Pb and Zn concentrations paralleled the rising and falling limits of the discharge hydrograph during the second event. The conventional asphalt lot is bordered by deciduous trees which overhang the lot. Leaves, twigs and other plant and animal organic debris accumulate on the pavement surface throughout the year. The relatively high COD levels recorded at this lot may be attributable to the perennial litterfall.

Conventional Concrete Lot --

Three stormwater surveys were conducted at the conventional concrete study lot, each in association with precipitation events; a summary of results is presented in Table 6. Observed runoff volumes ranged from 38 to 55 percent of recorded rainfall amounts, with an average of 46 percent for the three storm events. The runoff ratio was similar for each event and did not appear to be correlated to antecedent rainfall volumes. As with the previous pavements, detention times for the conventional concrete lot were uniform for each event, ranging from 14 to 18 minutes. The conventional concrete detention times are relatively long compared to the other impervious lot, reflecting the storage of rainfall in surface abstractions prior to runoff commencement.

The water quality of the surface runoff leaving the concrete lot was better than was expected at the project outset. The lot is consistently filled to capacity with cars during weekdays and was not swept during the study period. During the initial storm, discharge constituent values (except TSS and Pb) paralleled the discharge hydrograph; TSS and Pb did not evidence discernible trends. TSS, TN and Pb levels reflected a first-flush effect during the remaining events. A possible reason for the anomalously low concentrations of contaminants is the amount of stormwater storage and subsequent sedimentation provided on the surface of the lot. Surface depressions are abundant on all areas of the lot. During an interevent survey of the site, accumulations of grey silt were present at various locations, evidence of stormwater contaminant deposition. The flow monitoring weir throat was two inches (5 cm) above the surface of the pavement, creating a small reservoir during runoff events. The solids deposition behind the weir was approximately three-quarters of an inch (1.9 cm) deep during the dry period survey. Stormwater contaminants could conceivably have been retained in these areas and settled out with particulate matter or deposited during subsequent evaporation.

COMPARISON OF WATER QUALITY RESULTS

A significant factor in determining water quality performance characteristics of the various pervious and impervious lots is the variable pollutant load present on the pavement at the beginning of each event. The contaminant load originating on each study pavement is a function of dry weather accumulation rates and the stormwater hydraulic characteristics of each lot. Traffic type and density, presence of trees and other flora and the interval of time since the last rain large enough to rinse the pavement contribute to dry weather accumulation. A large amount of urban stormwater water quality data was collected and analyzed over the course of the study. Although the study lots were not ideal, the water quality data accurately reflect stormwater characteristics present during the natural and artificial runoff events which were monitored. The nonideal characteristics have been documented for each lot, and should be referred to before extrapolation of water quality characteristics to other sites.

Presented in Table 7 is a summary of average discharge concentrations obtained during the runoff events. Detailed data for each event are included in Appendix C. The following discussion highlights comparisons of water quality between previous and impervious lots.

Total Suspended Solids

Concentrations of TSS demonstrated a first-flush effect during a majority of storm events at both pervious and impervious lots. Peak concentrations were generally greater in the runoff from pervious lots, possibly due to erosion of the diversion channels at the porous asphalt lot and flushing of the ramp construction fines at the gravel trench lot. Flow-weighted average TSS concentrations observed in runoff from the conventional asphalt lot were lower than that from the porous asphalt or the gravel trench lot. As mentioned above, runoff from the conventional concrete lot was lower in TSS than from other lots.

Chemical Oxygen Demand

Intra-event trends of COD were markedly different between the pervious and impervious surfaces. Over 80 percent of the storm surveys on the porous lots indicated a first-flush effect, while there was no predominant trend of COD on the impervious lots. As with the TSS values, peak concentrations of COD were generally greater on the pervious lots, possibly for the same reasons.

Total Nitrogen and Total Kjeldahl Nitrogen

Intra-event trends of TN were similar on pervious and impervious lots. There was no significant difference in average TN concentrations between the pervious and impervious surfaces. Average concentrations of TKN in the runoff from the conventional concrete lot were lower than in runoff from pervious facilities. Peak concentrations observed in runoff from the conventional asphalt lot were similar to peak values recorded for the pervious facilities.

TABLE 7

SUMMARY OF CONSTITUENT CONCENTRATIONS

Pavement Type	Average Concentration (mg/l) First Event	Second Event	Third Event	Flow-weighted Average (mg/l)
TSS				
Porous Asphalt	389	134	44.1	175
Lattice Block	29.1	17.4	30.4	24.5
Gravel Trench	115	417	190	240
Conventional Asphalt	39.7	51.7	--	43.0
Conventional Concrete	12.2	17.6	11.7	13.7
COD				
Porous Asphalt	31.3	15.6	29.2	24.8
Lattice Block	25.1	33.5	44.4	33.4
Gravel Trench	38.8	113	77.0	77.6
Conventional Asphalt	19.9	57.0	--	30.0
Conventional Concrete	18.0	15.8	30.3	19.6
TN				
Porous Asphalt	1.82	2.22	4.71	2.96
Lattice Block	1.48	2.30	2.09	1.79
Gravel Trench	1.45	2.28	2.17	2.00
Conventional Asphalt	--[a]	2.88	--	2.88
Conventional Concrete	--	--	--	--

TABLE 7 (Concluded)

Pavement Type	Average Concentration (mg/l)			Flow-weighted Average (mg/l)
	First Event	Second Event	Third Event	
TKN				
Porous Asphalt	0.93	1.46	3.53	2.24
Lattice Block	1.25	1.70	1.79	1.57
Gravel Trench	1.09	1.55	1.56	1.42
Conventional Asphalt	0.87	2.33	--	1.27
Conventional Concrete	0.66	0.30	0.25	0.54
Lead				
Porous Asphalt	0.024	0.007	0.013	0.014
Lattice Block	0.009	0.015	0.011	0.012
Gravel Trench	0.025	0.042	0.012	0.025
Conventional Asphalt	0.009	0.020	--	0.012
Conventional Concrete	0.020	0.033	0.008	0.021
Zinc				
Porous Asphalt	0.020	0.018	0.054	0.031
Lattice Block	0.026	0.022	0.008	0.020
Gravel Trench	0.050	0.146	0.075	0.090
Conventional Asphalt	0.007	0.026	--	0.012
Conventional Concrete	0.033	0.008	0.010	0.007

[a] Constituent was not analyzed.

Lead and Zinc

Intra-event trends of metals were similar for the pervious and nonpervious lots. Peak concentrations of zinc were significantly greater at the gravel trench lot while peak lead levels were anomolously high only at the conventional concrete lot during the initial storm event. The presence of metals in urban stormwater runoff is generally attributed to automobile pollution, including exhaust, fluid leaks and mechanical wear. The gravel trench lot had the highest flow-weighted average concentration of both lead and zinc. As was presented in Table 1, this lot had the greatest automobile traffic per day, however, the high lead concentrations from the gravel trench site may not be directly attributable to the lot's traffic, which consists almost entirely of late model cars using unleaded gas. Average zinc values were greater in the runoff from the pervious lots than from the nonpervious lots.

Organic Priority Pollutants

Composited samples representing the rising, peak and falling portions of the runoff hydrograph for the lattice block lot were taken on March 2, 1982 and analyzed. Toluene was the only purgeable priority pollutant found in all three samples, and at very low concentrations (0.7, 0.7, and 0.4 μg/l, respectively). Chloroform was found at 0.3 μg/l in the sample representing the peak portion of the runoff. Using a computerized library search procedure, the peaks of the three chromatograms were examined and very low concentrations (probably < 5 μg/l) of small (C_6 and below) ketones and hexane were identified.

The results of the analyses of the three samples for semivolatile priority pollutants in the lattice block lot are shown in Table 8. All of the compounds detected were at very low concentrations except for several of the phthalates, which are widely used plasticising agents.

Samples representative of the first and second half of the base discharge hydrograph from the porous asphalt lot were taken on June 1, 1982, during a simulated rainfall test and analyzed along with a control sample of water being sprayed onto the pavement surface. In only one case was a purgeable priority pollutant found: the control sample (City of Austin municipal supply) contained 9 μg/l of chloroform. Compounds other than priority pollutants found in the samples consisted of hydrocarbons, ketones and possible 3-methyltetrohydrofuran (< 8-10 μg/l). These chemicals were in all three samples. The control sample also contained a C_6 - C_8 ether or alcohol at about 5 μg/l.

Data indicative of the level of semivolatile organics in the porous asphalt lot underflow are shown in Table 9. With the exception of two of the phthalates, which were also present in the control water, all the compounds were present at low concentrations.

The GC/MS chromatograms for the two underflow samples and the control sample were also examined for other components. Only major peaks, arbitrarily defined as > 50X noise were examined (this would be compounds of 3-5 μg/l and above). With the exception of one group of compounds, nothing of significance was found. All three samples had cyclohexane and cyclohexane derivatives, such as ketones, alcohols and halogenated compounds.

TABLE 8

SEMIVOLATILE COMPOUNDS IN LATTICE BLOCK LOT RUNOFF[1]

Compound	Sampling Interval of Hydrograph		
	Rising	Peak	Falling
DIMETHYLPHTHALATE			
DIETHYLPHTHALATE	0.8	0.5	0.6
DIBUTYLPHTHALATE	34.0	19.0	13.0
BUTYLBENZYLPHTHALATE	2.6	1.5	1.2
BIS(2-ETHYLHEXYL)PHTHALATE	21.0	23.0	9.8
DI-N-OCTYLPHTHALATE	3.7	4.3	2.9
NAPHTHALENE	0.5	0.4	0.4
ACENAPHTHYLENE			
ACENAPHTHENE			
FLUORENE	0.1	0.1	
PHENANTHRENE	0.3	0.3	
ANTHRACENE	0.1	0.1	
FLUORANTHENE	0.3		
PYRENE			
CHRYSENE			
BENZO(A)ANTHRACENE			
BENZOFLUORANTHENE (BOTH ISOMERS UNRESOLVED)			
BENZO(A)PYRENE			
INDENO(1,2,3,C,D)PYRENE			
DIBENZO(A,H)ANTHRACENE			
BENZO(G,H,I)PERYLENE			

TABLE 8 (Cont'd)

Compound	Sampling Interval of Hydrograph		
	Rising	Peak	Falling
NITROBENZENE			
ISOPHORONE	0.2	0.1	
2,6-DINITROTOLUENE			
2,4-DINITROTOLUENE			
N-NITROSODIPROPYLAMINE			
N-NITROSODIPHENYLAMINE (AS DIPHENYLAMINE)	1.0	1.2	0.9
4-CHLOROPHENYL PHENYL ETHER			
4-BROMOPHENYL PHENYL ETHER			
2-CHLORONAPHTHALENE			
M-DICHLOROBENZENE (UNSURE OF ISOMER)	0.1		
P-DICHLOROBENZENE (UNSURE OF ISOMER)	0.1		
O-DICHLOROBENZENE (UNSURE OF ISOMER)	0.1		
1,2,4-TRICHLOROBENZENE	0.1		
HEXACHLOROBENZENE			
HEXACHLOROETHANE			
HEXACHLOROBUTADIENE			
HEXACHLOROCYCLOPENTADIENE			
PHENOL		0.3	0.3
2-CHLOROPHENOL			
4-CHLORO-3-METHYLPHENOL			
2,4,6-TRICHLOROPHENOL			

TABLE 8 (Concluded)

Compound	Sampling Interval of Hydrograph		
	Rising	Peak	Falling
4,6-DINITRO-2-METHYLPHENOL			
PENTACHLOROPHENOL			
2- or 4-NITROPHENOL			
2,4-DIMENTHYLPHENOL			
2,4-DICHLOROPHENOL			
2,4-DINITROPHENOL			

[1] All values in μg/l. Blank spaces indicate the compound was not detected.

TABLE 9

SEMIVOLATILE COMPOUNDS IN POROUS ASPHALT UNDERFLOW[1]

Compound	Sampling Interval of Hydrograph		
	Rising	Peak	Falling
DIMETHYLPHTHALATE		0.3	
DIETHYLPHTHALATE	0.6	0.4	0.4
DIBUTYLPHTHALATE	20.0	9.8	11.5
BUTYLBENZYLPHTHALATE	1.3	1.6	1.5
BIS(2-ETHYLHEXYL)PHTHALATE	12.0	9.7	8.4
DI-N-OCTYLPHTHALATE	0.5	0.8	1.7
NAPHTHALENE	0.4	0.4	0.3
ACENAPHTHYLENE			
ACENAPHTHENE			
FLUORENE	0.1	0.1	
PHENANTHRENE		0.3	
ANTHRACENE		0.3	
FLUORANTHENE	0.6	0.3	0.4
PYRENE	0.9		1.0
CHRYSENE	1.5	1.1	
BENZO(A)ANTHRACENE	0.6	0.5	
BENZOFLUORANTHENE (BOTH ISOMERS UNRESOLVED)	0.5	0.4	
BENZO(A)PYRENE		0.5	0.4
INDENO(1,2,3,C,D)PYRENE			
DIBENZO(A,H)ANTHRACENE			
BENZO(G,H,I)PERYLENE		0.6	

TABLE 9 (Cont'd)

Compound	Sampling Interval of Hydrograph		
	Rising	Peak	Falling
NITROBENZENE			
ISOPHORONE	1.3	1.1	
2,6-DINITROTOLUENE			
2,4-DINITROTOLUENE			
N-NITROSODIPROPYLAMINE			
N-NITROSODIPHENYLAMINE (AS DIPHENYLAMINE)	1.3	1.0	1.8
4-CHLOROPHENYL PHENYL ETHER			
4-BROMOPHENYL PHENYL ETHER			
2-CHLORONAPHTHALENE			
M-DICHLOROBENZENE (UNSURE OF ISOMER)			
P-DICHLOROBENZENE (UNSURE OF ISOMER)			
O-DICHLOROBENZENE (UNSURE OF ISOMER)			
1,2,4-TRICHLOROBENZENE			
HEXACHLOROBENZENE			
HEXACHLOROETHANE			
HEXACHLOROBUTADIENE			
HEXACHLOROCYCLOPENTADIENE			
PHENOL			
2-CHLOROPHENOL			
4-CHLORO-3-METHYLPHENOL			
2,4,6-TRICHLOROPHENOL			

TABLE 9 (Concluded)

Compound	Sampling Interval of Hydrograph		
	Rising	Peak	Falling
4,6-DINITRO-2-METHYLPHENOL			
PENTACHLOROPHENOL			
2- or 4-NITROPHENOL			
2,4-DIMENTHYLPHENOL			
2,4-DICHLOROPHENOL			
2,4-DINITROPHENOL			

[1] All values in µg/l. Blank spaces indicate the compound was not detected.

STORMWATER SIMULATION RESULTS

Stormwater hydraulics for each pavement type were simulated with the revised PORPAV, which was calibrated for each lot using one set of observed runoff data. The calibrated coefficients were held constant during the simulation of the remaining events for model verification. A list of required input data for PORPAV is presented in Table 10. Pavement characteristics such as pavement length, width, depth and the collection drain capacity were obtained from onsite and construction measurements. Other parameters such as the surface roughness coefficient, volume of dead storage on the pavement and pavement porosity were estimated. The record of observed inflow (rainfall or sprinkler spray) was input to PORPAV for each event. Calibration of the model was initialized by varying values of the estimated parameters to reproduce the observed runoff volume. Generally this was accomplished by adjusting the volume of surface storage for the impervious lots and the base storage (the product of depth and porosity) for the pervious lots. The second objective was to reproduce the observed peak runoff rate. Surface runoff rates were adjusted by varying the estimates of and the roughness coefficient. For the porous asphalt and gravel trench lots the coefficient of permeability for the base layer was varied to reproduce the observed peak base discharge rate.

Simulation results were evaluated on the basis of reproducing observed runoff volumes, peak discharges and response time. Input values for each simulation are presented in Table 11.

Porous Asphalt Lot

Calibration of PORPAV was conducted using records of sprinkler inflows and discharge measurements from the initial stormwater event. The simulation results are compared to observed values in Table 12. The cumulative runoff volume and the peak discharge rate were reproduced quite well as demonstrated in Fig. 32. The simulated temporal response indicated by the time to peak and detention time, was more rapid than the recorded values, attributable in part to the travel time associated with the exterior drainage channels which were not modeled with PORPAV. Another point to consider is that the resolution of temporal repsonse is dependent on the duration of the simulation time step. Simulation response times within ± one time step of the observed times represent accurate simulations. The subsequent verification simulation of the 1 June 1982 event, presented in Fig. 33, did not reproduce observed values as well as the calibration set. The discrepancies between the two discharge hydrographs reflect the difference in hydrologic response between the two data sets. The event of 5 April 1982 was not simulated, as the observed sprinkler inflow, which is used as input to PORPAV, was 28 percent less than the observed discharge.

Lattice Block Lot

Three sprinkler generated storm events at the lattice block lot were modeled. The results are compared to observed values in Table 13. The lattice block lot was simulated using a 2-layer representation. A thin surface layer was utilized which had a different permeability rate than did the underlaying base layer. This approach facilitated modeling the nonuniform surface permeability rate of the sandy loam which comprises a large percent of the surface as well as the storage media in the lot. A comparison of discharge hydrographs for the calibration data set is presented in

TABLE 10

INPUT DATA FOR PORPAV SIMULATIONS

Element	Parameter	Unit
Rainfall rate	Magnitude	in/hr
Pavement surface	Length	ft
	Width	ft
	Slope	ft/ft
	Area	ft^2
	Permeability	in/hr
	Depth	in
	Porosity	ft^3/ft^3
	Initial and dead storage	in
	Manning's n coefficient of roughness	$ft^{1/6}/s$
Pavement base	Permeability	in/hr
	Depth	in
	Porosity	ft^3/ft^3
	Initial and dead storage	in
	Collection drain capacity	in/hr
Natural soil	Initial and final infiltration rate	in/hr
	Horton's infiltration decay coefficient	hr^{-1}

TABLE 11

SUMMARY OF SIMULATION INPUT VALUES

Pavement Type	Permeability (in/in)	Depth (in)	Porosity (percent)	Initial Storage (in)	Dead Storage (in)
Porous Asphalt					
Surface Layer	500	3	25	0	0
Base Layer	15,000	20	35	0	0.317
Surface slope = 2.6 percent					
Manning's n = 0.02					
Lattice Block					
Surface Layer	0.68	0.5	15	0	0
Base Layer	5.0	3.5	15	0	0
Surface slope = 4.2 percent					
Manning's n = 0.4					
Gravel Trench					
Surface Layer	30	3	25	0	0
Base Layer	50,000	36	25	0	0
Base slope = 5.0 percent					
Manning's n = 0.1					
Conventional Asphalt					
Surface Layer	0.001	3	5	0	0.05
Surface slope = 3 percent					
Manning's n = 0.02					
Conventional Concrete					
Surface Layer	0.001	2	1	0	0.30
Surface slope = 1.5 percent					
Manning's n = 0.02					

TABLE 12

SIMULATION RESULTS
POROUS ASPHALT LOT

	Peak Flow (cfs)	Time to Peak (min)	Runoff Volume (cubic feet)	Detention Time (min)
CALIBRATION				
STORM 1 (3/22/82)				
Observed	0.269	58	815	42
Simulated	0.273	50	815	28
Deviation	+0.004	-8	0	-14
VERIFICATION				
STORM 2 (6/1/82)				
Observed	0.237	53	721	42
Simulated	0.514	55	1409	25
Deviation	+0.283	+2	+688	-17

1 cfs = 28.32 lps

1 ft^3 = 28.32 l

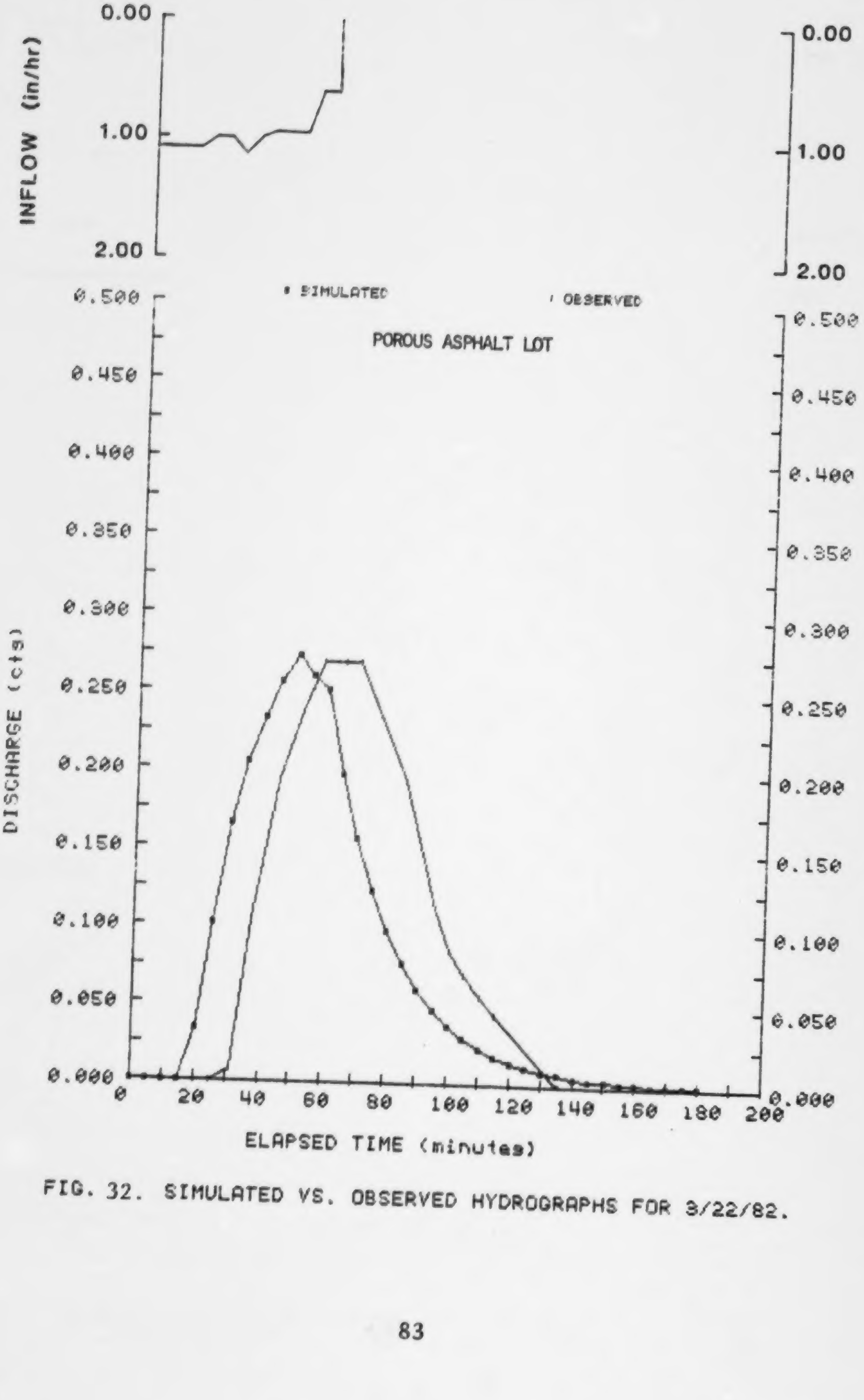


FIG. 32. SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/22/82.

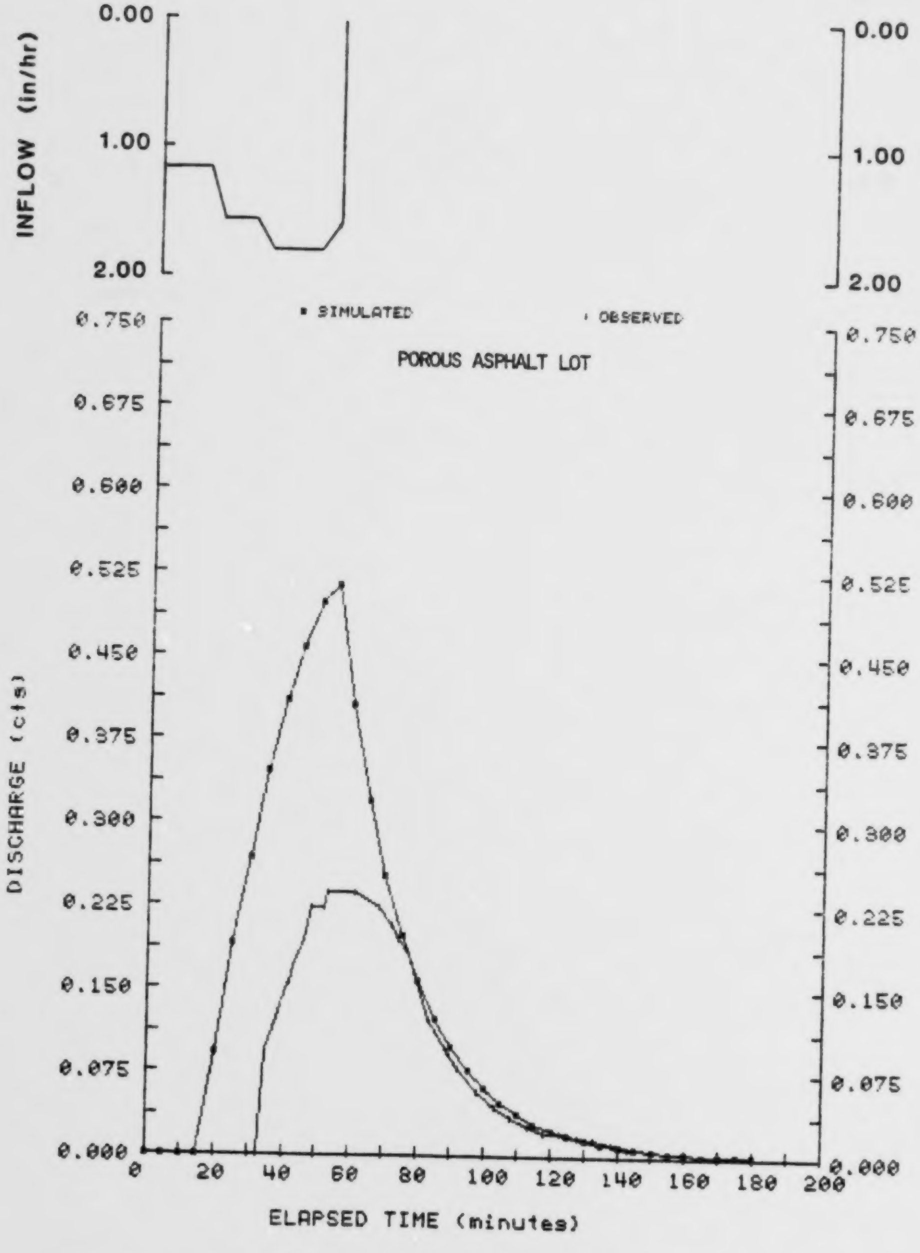


FIG. 33 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 6/1/82.

TABLE 13

SIMULATION RESULTS
LATTICE BLOCK LOT

	Peak Flow (cfs)	Time to Peak (min)	Runoff Volume (cubic feet)	Detention Time (min)
CALIBRATION				
STORM 1 (3/2/82)				
Observed	0.034	55	101	11
Simulated	0.052	75	96	18
Deviation	+0.018	+20	-5	+7
VERIFICATION				
STORM 2 (3/11/82)				
Observed	0.078	40	201	12
Simulated	0.063	30	184	6
Deviation	-0.015	-10	-17	-6
VERIFICATION				
STORM 3 (3/18/82)				
Observed	0.113	24	129	11
Simulated	0.185	35	281	4
Deviation	+0.072	+11	+152	-7

1 cfs = 28.32 lps
$1\ ft^3 = 28.32$ l

Fig. 34. The runoff volume and the recession limb of the hydrograph are well reproduced, while the peak runoff rate was overestimated. The simulated temporal response lagged slightly the observed response, although the hydrograph decay was tracked well. The observed discharge characteristics of the second runoff event presented in Fig. 35, were well simulated. The simulated hydraulic response for the third event was quite different from the observed results, as compared in Fig. 36. The bimodal peak of the simulated discharge hydrograph reflects the influence of the second burst of recorded inflow, whereas the observed hydrograph does not. This may be an artifact of the sampling time interval between discharge estimates, i.e., possibly the second peak occurred but was not monitored; this may also explain the discrepancy between observed and simulated volumes.

Gravel Trench Lot

Three runoff events generated with water trucks were simulated for the gravel trench lot. For each case the runoff from the contributing asphalt lot was simulated with PORPAV and the surface discharge was subsequently used as input to the gravel trench simulation, hence, characteristics for both facilities had to be determined. A summary of simulation results is presented in Table 14. Coefficients of base permeability and dead storage on the asphalt lot and in the gravel trench were determined by calibrating PORPAV with the initial runoff event data. The resulting hydrograph is presented in Fig. 37. Runoff characteristics were reproduced quite well for the second event, as displayed in Fig. 38. However, incorporating the same physical characteristics of the asphalt and gravel trench for the final event simulation yielded a less satisfactory comparison, presented in Fig. 39. The major discrepencies in the two hydrographs of the third event occur during the periods of water release from the water trucks, possibly introduced by utilizing a constant inflow rate during this period in the simulation. Simulated detention times for all three events were within one time step (5 minutes) of the observed value.

Conventional Asphalt Lot

Data from sprinkler generated runoff event of 11 May 1982 were utilized to calibrate PORPAV for the conventional asphalt lot. Due to the rapid hydraulic response of the lot, a 1-minute time step was employed. As presented in Fig. 40, and Table 15, the resulting hydrograph tracks the observed discharge rates quite well. The cumulative volume, time to peak and detention time estimates are all very close to observed values, while the simulated peak discharge rate was approximately 0.03 cfs (0.8 l/s) greater than the observed peak. The natural precipitation event of 3 March 1982 was subsequently simulated; discharge hydrographs are compared in Fig. 41. While the simulated temporal response was similar, estimates of cumulative volume and the peak discharge rate were significantly lower than observed values.

A possible explanation for the discrepancy of the peak discharge rate concerns the rainfall measurement interval. The discrete (5-minute) interval between cumulative rainfall measurements necessitates averaging over the interval to produce an estimate of average intensity. This process dampens out short intense bursts of rainfall which contribute to rapid discharge rates such as that observed during the 3 June 1981 event. This data collection phenomena, however, would not account for such a large volume discrepancy between the simulated and observed results.

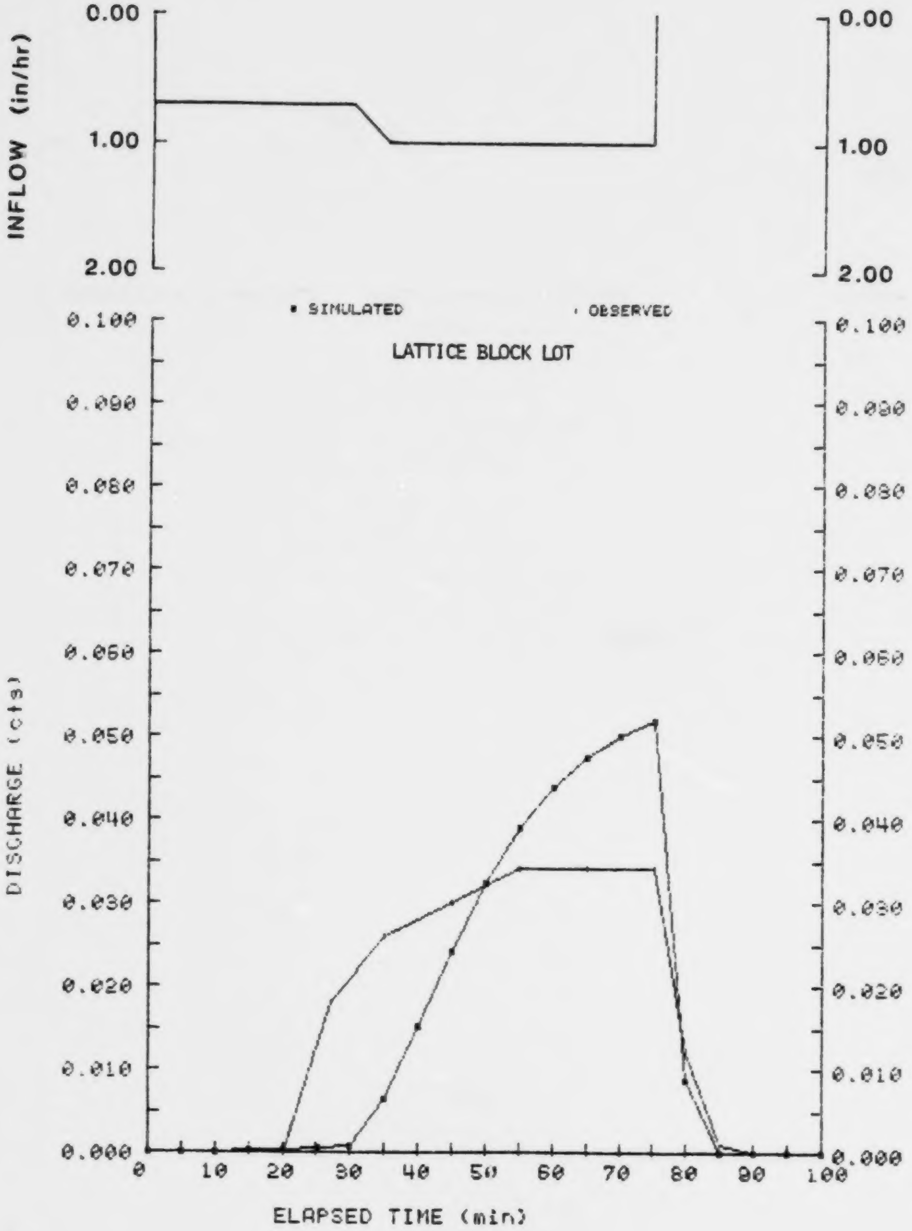


FIG. 34 . SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/02/82.

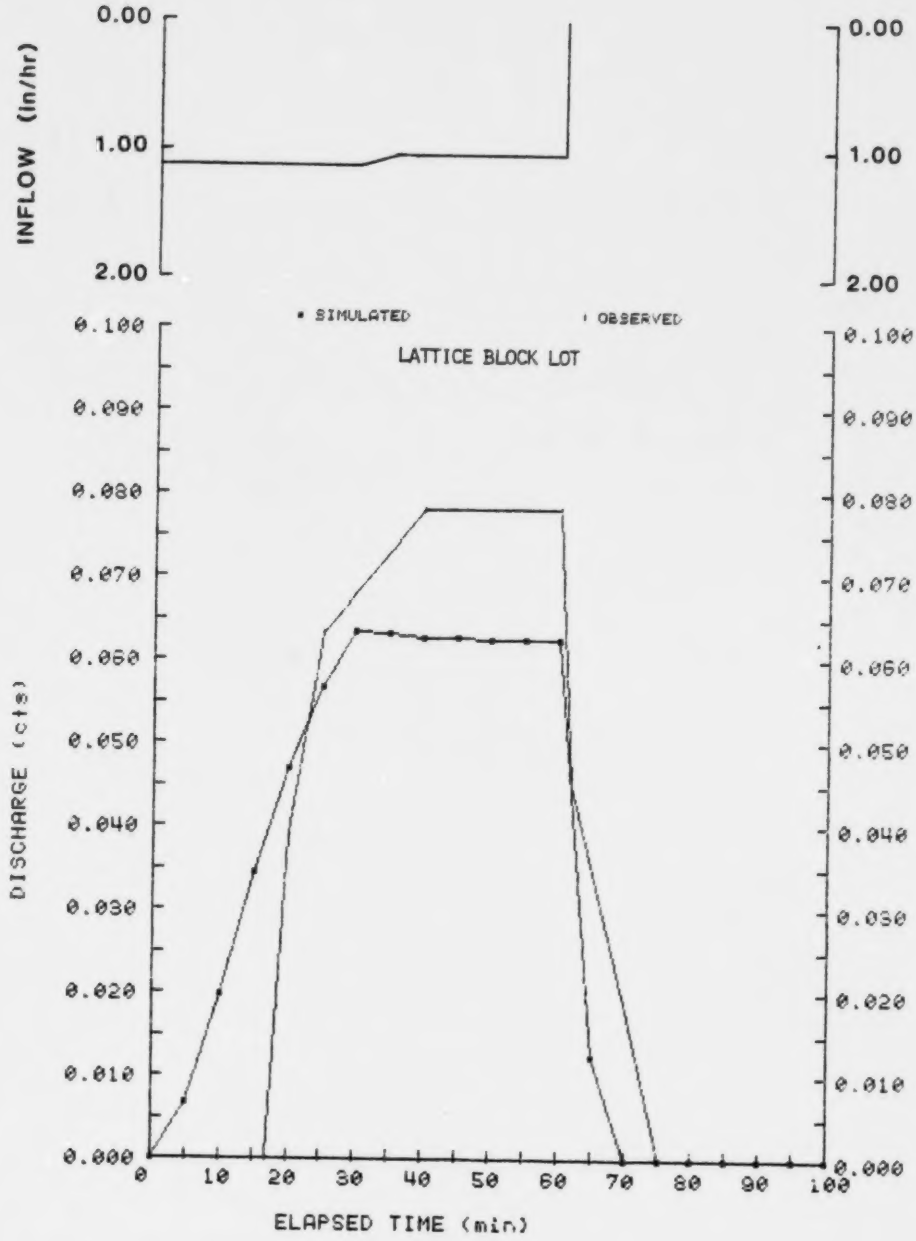


FIG. 35 . SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/11/82.

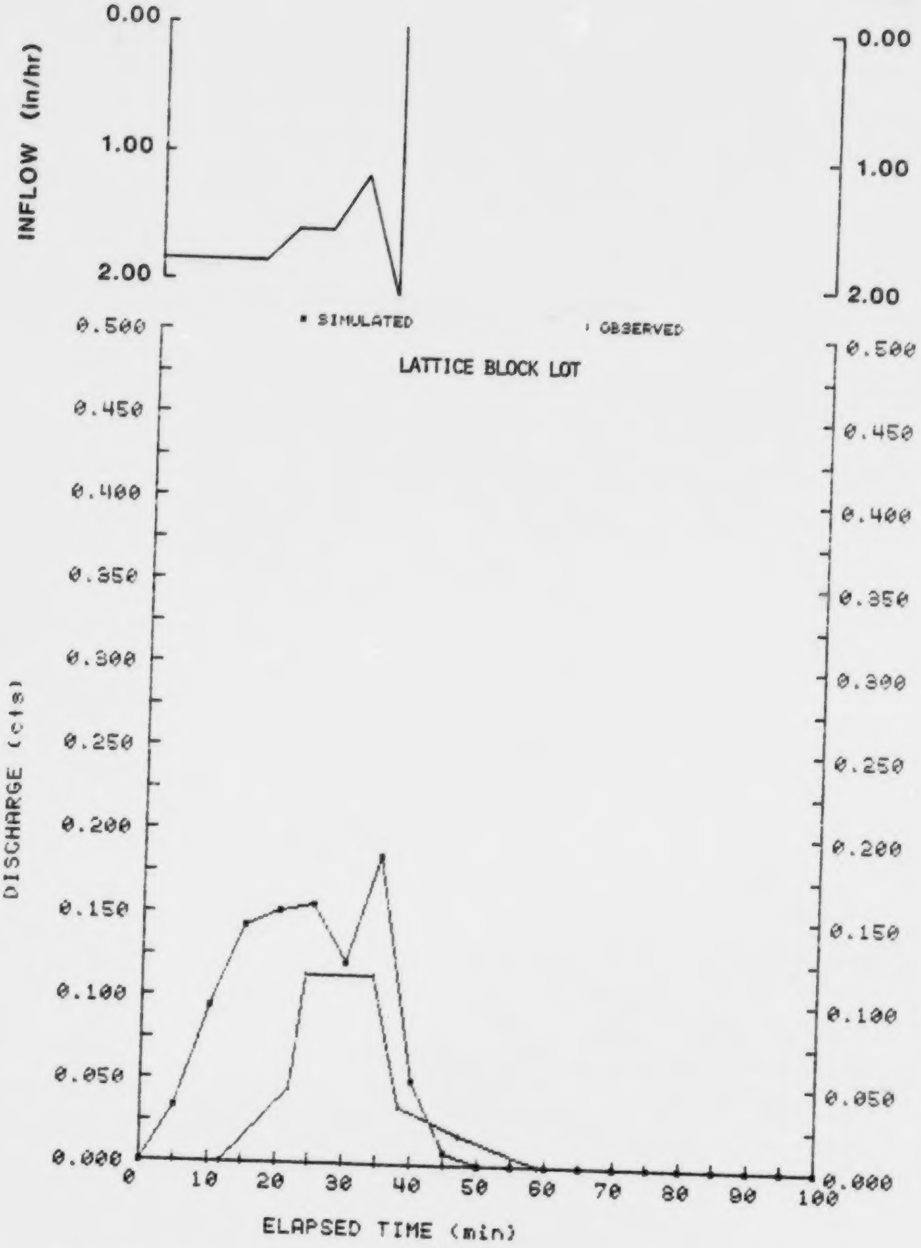


FIG. 36 . SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/18/82.

TABLE 14

SIMULATION RESULTS
GRAVEL TRENCH LOT

	Peak Flow (cfs)	Time to Peak (min)	Runoff Volume (cubic feet)	Detention Time (min)
CALIBRATION				
STORM 1 (3/3/82)				
Observed	0.44	60	1960	29
Simulated	0.497	90	2107	24
Deviation	+0.057	+30	+147	-5
VERIFICATION				
STORM 2 (3/19/82)				
Observed	0.580	66	1693	24
Simulated	0.487	70	1650	24
Deviation	-0.093	+4	-43	0
VERIFICATION				
STORM 3 (4/7/82)				
Observed	1.667	55	1861	19
Simulated	0.472	60	1448	23
Deviation	-1.195	+5	-413	+4

1 cfs = 28.32 lps
1 ft^3 = 28.32 l

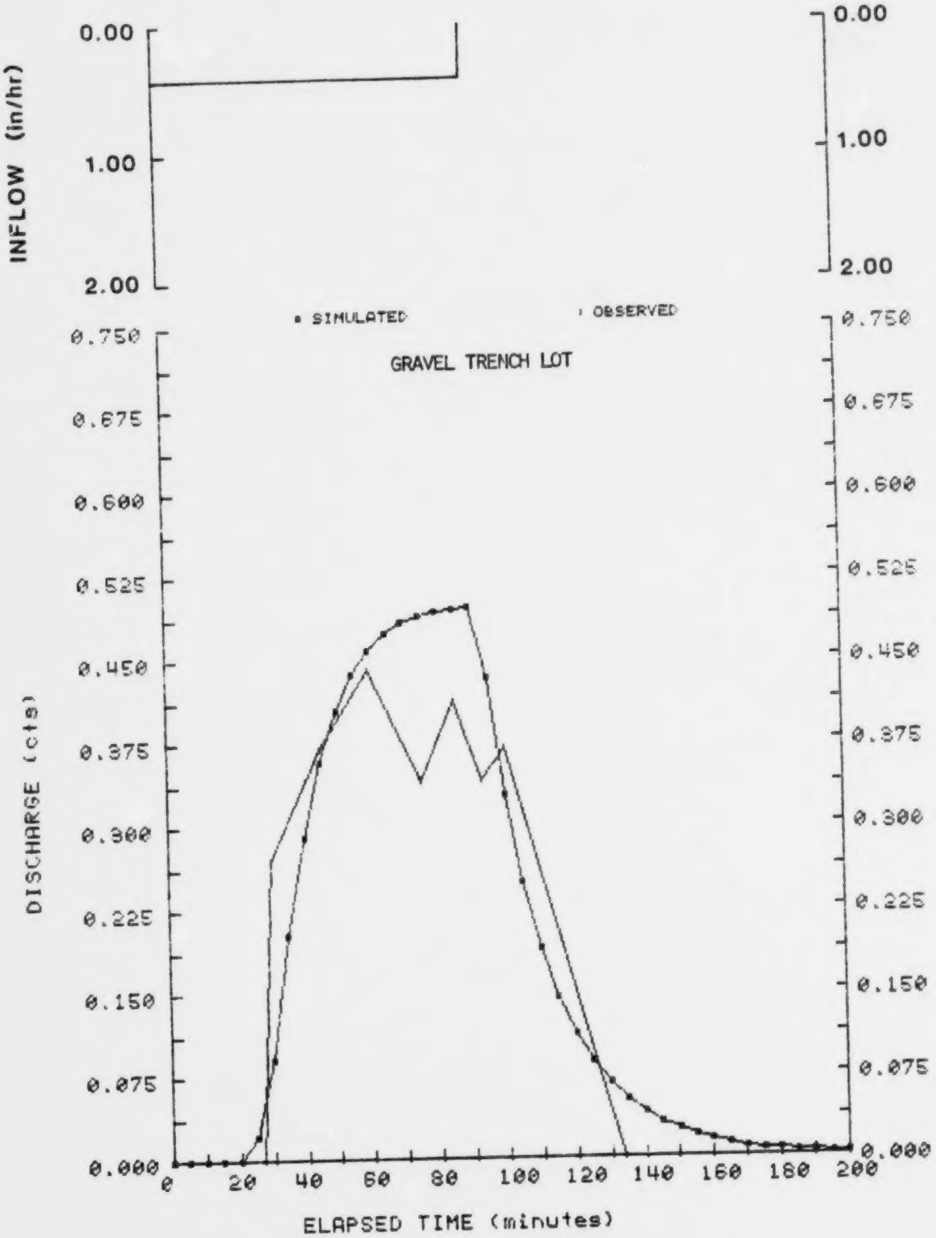


FIG. 37 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/3/82.

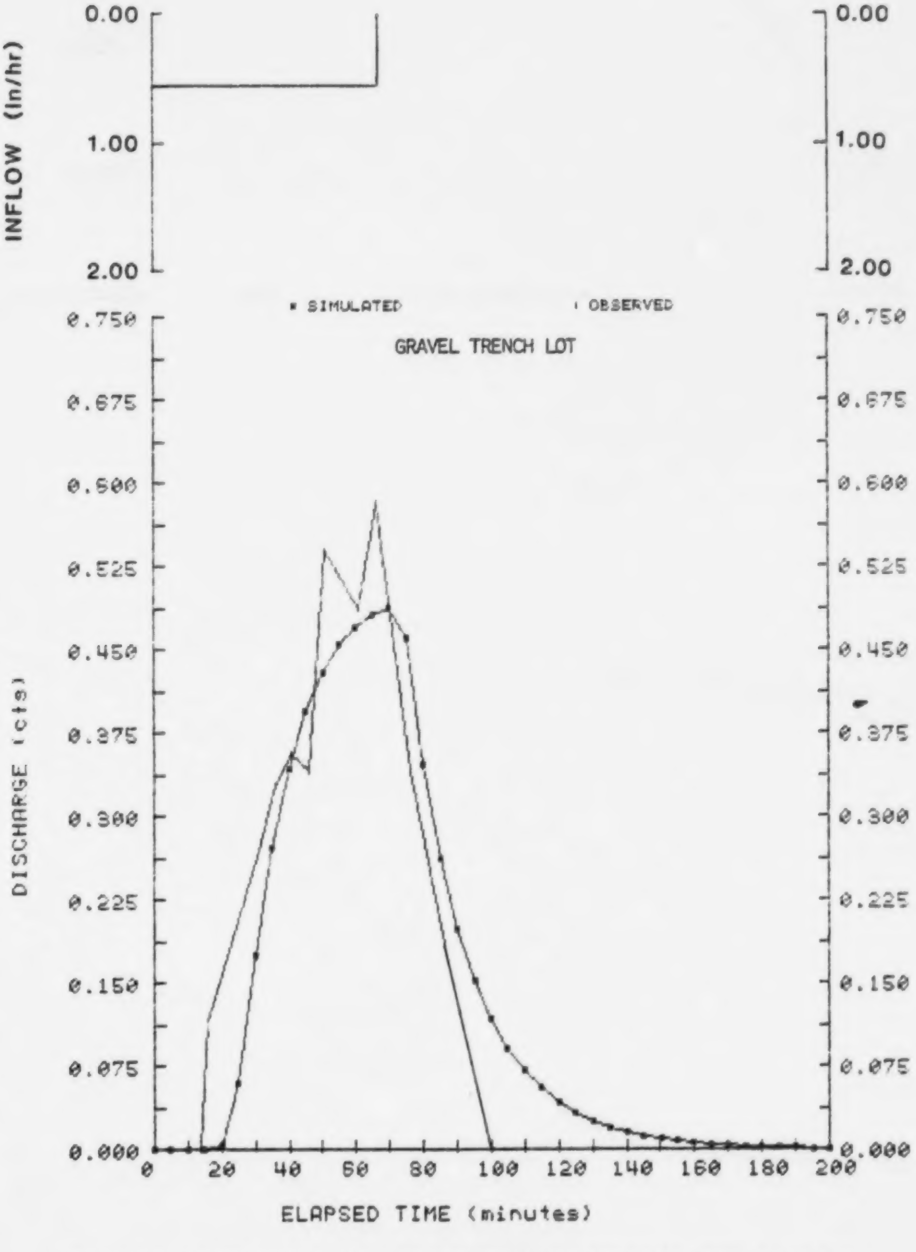


FIG. 38 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/18/82.

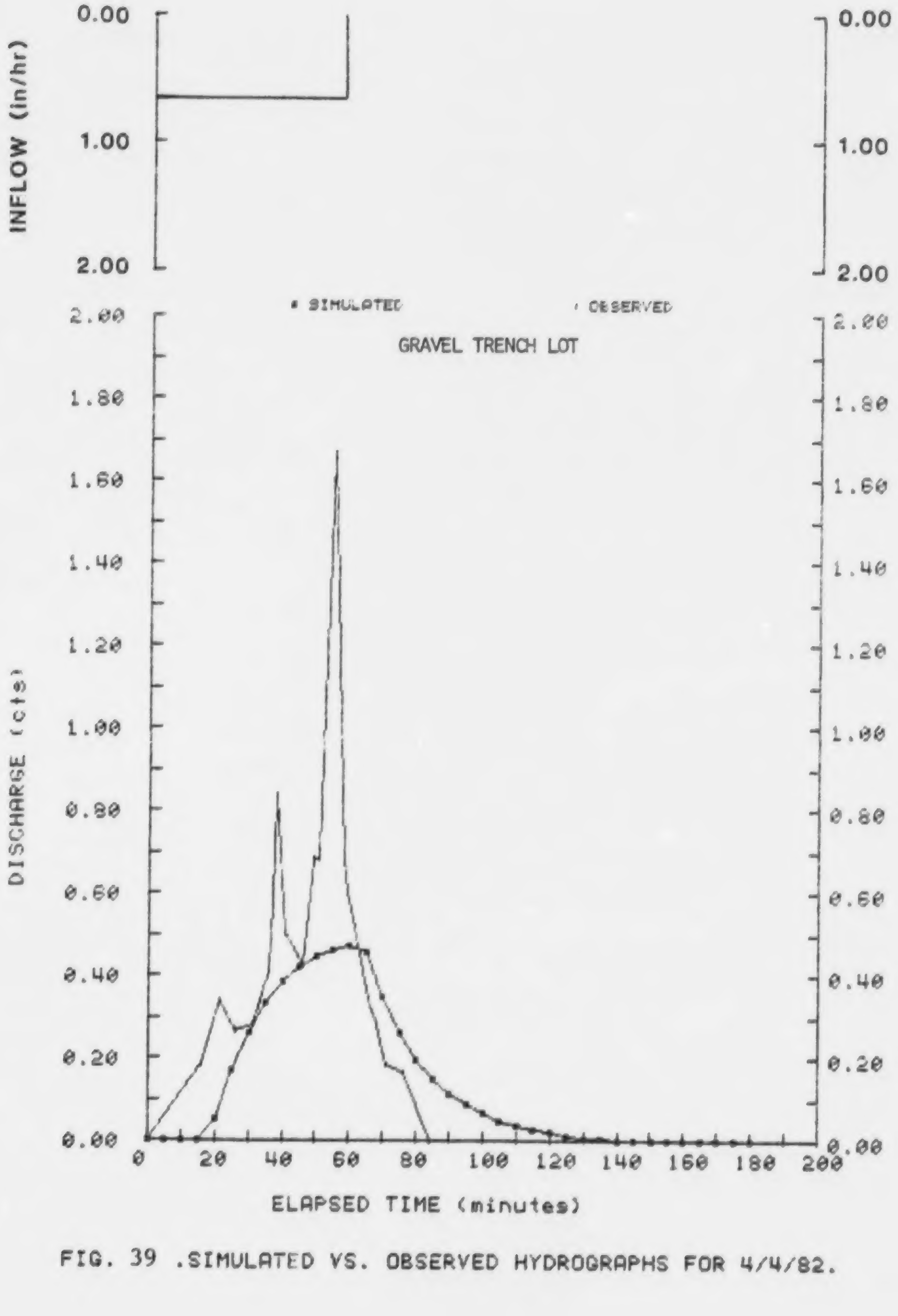


FIG. 39 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 4/4/82.

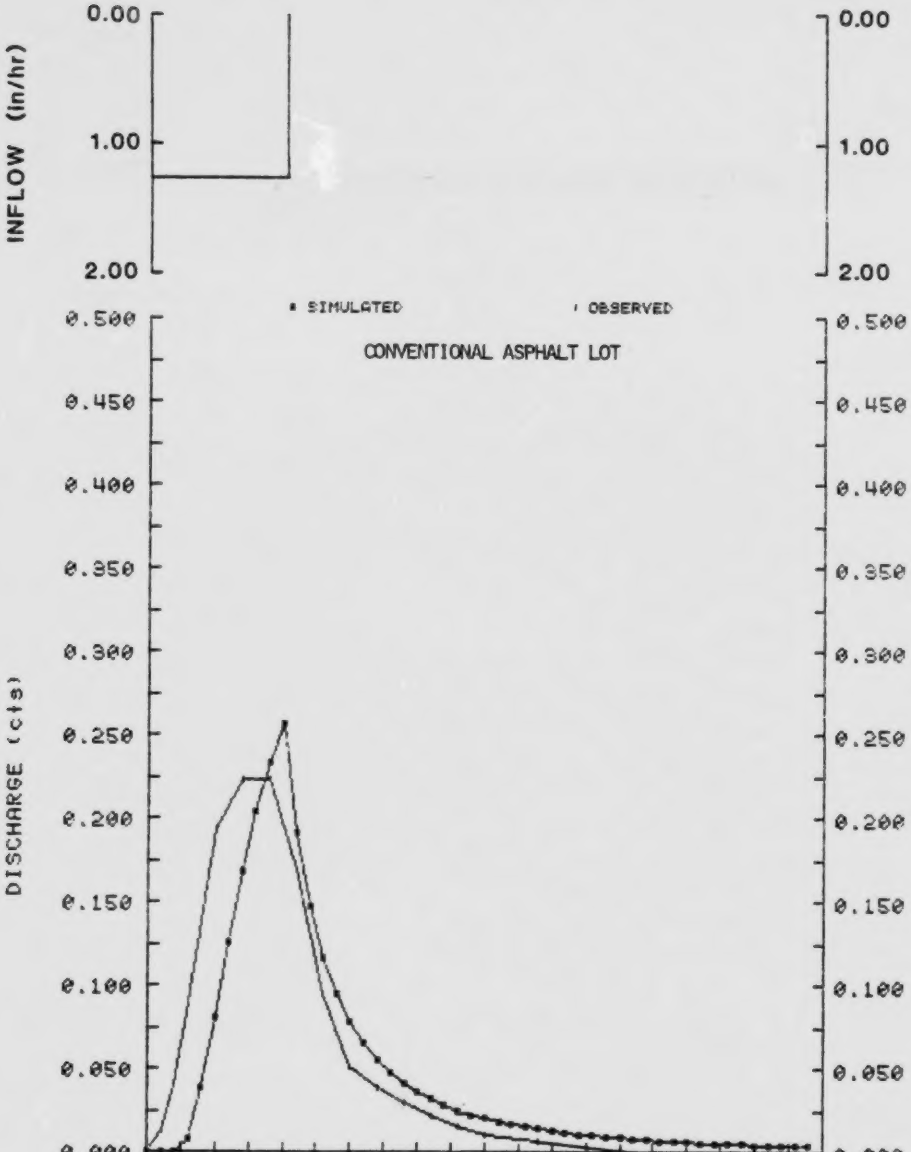


FIG. 40 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 5/11/82.

TABLE 15

SIMULATION RESULTS
CONVENTIONAL ASPHALT LOT

	Peak Flow (cfs)	Time to Peak (min)	Runoff Volume (cubic feet)	Detention Time (min)
VERIFICATION				
STORM 1 (6/3/81)				
Observed	0.84	53	368	1
Simulated[1]	0.460	60	265	4
Deviation	-0.380	+7	-103	+3
CALIBRATION				
STORM 2 (5/11/82)				
Observed	0.223	7	138	5
Simulated	0.257	10	140	8
Deviation	+0.034	+3	+2	+3

[1] Observed discharge was greater than the observed rainfall which was input to PORPAV.

1 cfs = 28.32 lps

1 ft^3 = 28.32 l

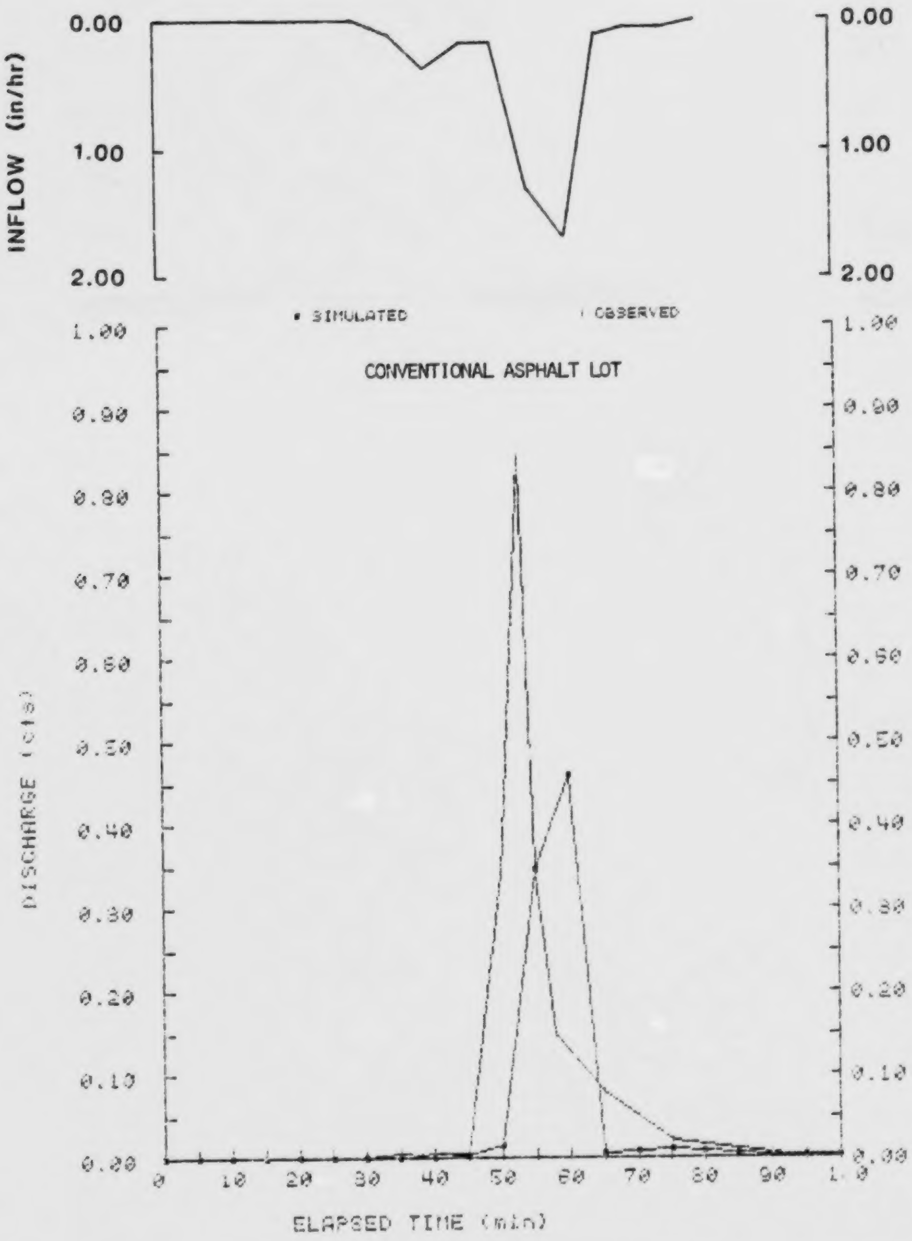


FIG. 41. SIMULATED VS. OBSERVED HYDROGRAPHS FOR 6/03/81.

Conventional Concrete Lot

Each of the stormwater events monitored at the concrete lot were produced by natural rainfall. Hydraulic data obtained during the first stormwater survey was used to calibrate PORPAV; the remaining two stormwater events were simulated using the calibrated version. Simulation results are presented in Table 16 and Figs. 42 through 44. While the cumulative discharge volumes and the temporal response of the stormwater events were accurately simulated, the simulated hydrographs do not reflect the dampening affected by the depression storage on the lot.

PREDICTION OF WATER QUALITY

Methodology

Prediction of stormwater runoff water quality can be a valuable technique in assessing control strategies. Several methodologies have been employed by previous researchers. Computer simulation describing the accumulation, wash-off and transport of stormwater contaminants has been advanced through the development of EPA's Storm Water Management Model (SWMM) (11) and others. However, the complexities of contaminant accumulation, decay and transport mechanisms generally preclude deterministic evaluation.

The inference of stormwater quality from hydraulic characteristics of porous pavement facilities is a possible resolution to simulation difficulties encountered in describing runoff water quality phenomena. The association of contaminant load and runoff flow has been explored for various relationships. Winslow and Espey (17) and others have reported linear regression equations relating constituent concentration to instantaneous streamflow measurements. Smolenyak (18) determined coefficients of a power equation to describe the relationship between instantaneous flow and the mass of contaminant discharged with the stormwater (referred to as mass loading). Diniz and Espey (19) applied a power equation to the relationship between the mass loading and the cumulative flow for urban stormwater data. This same approach was incorporated in this study. Regression relationships between constituent mass loading and cumulative discharge were investigated. The three nonlinear and one linear regression models utilized are presented below.

Regression Model	Equation
1	$Y = A + B(\log_{10}(X))$
2	$Y = A \exp(BX)$
3	$Y = A X^B$
4	$Y = A + BX$

where X is the cumulative discharge, in ft^3 ($1\ ft^3 = 0.028.316\ m^3$);

Y is the cumulative consitituent load, in pounds (1 pound = 0.454 kg); and,

A and B are regression coefficients.

TABLE 16

SIMULATION RESULTS
CONVENTIONAL CONCRETE LOT

	Peak Flow (cfs)	Time to Peak (min)	Runoff Volume (cubic feet)	Detention Time (min)
CALIBRATION				
STORM 1 (3/3/81)				
Observed	0.20	58	598	18
Simulated	0.939	55	729	12
Deviation	+0.739	-3	+131	-6
VERIFICATION				
STORM 2 (6/3/81)				
Observed	0.10	30	361	14
Simulated	0.482	30	354	15
Deviation	+0.382	0	-7	+1
VERIFICATION				
STORM 3 (10/7/81)				
Observed	0.07	30	225	17
Simulated	0.350	20	195	13
Deviation	+0.28	-10	-30	-4

1 cfs = 28.32 lps
1 ft^3 = 28.32 l

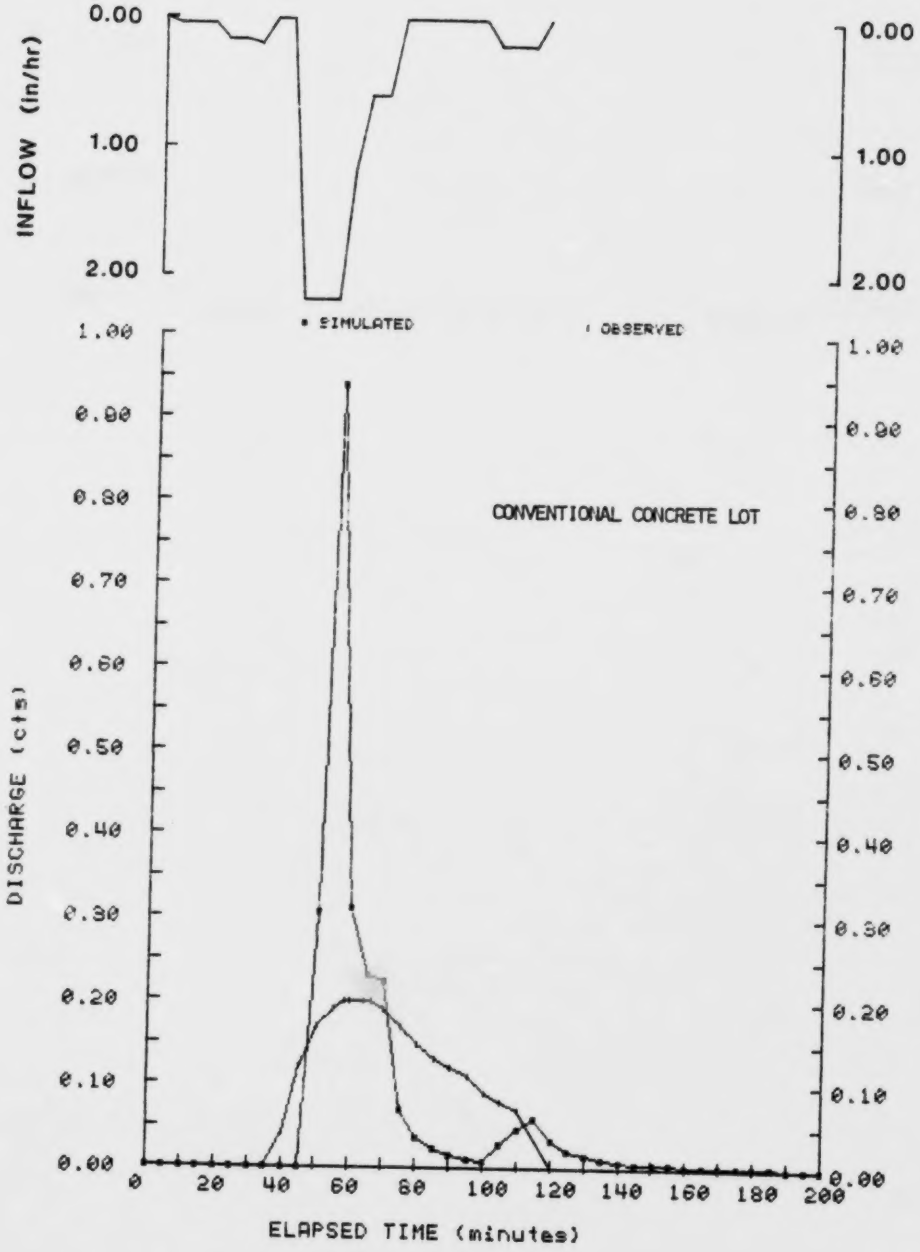


FIG. 42 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 3/3/81.

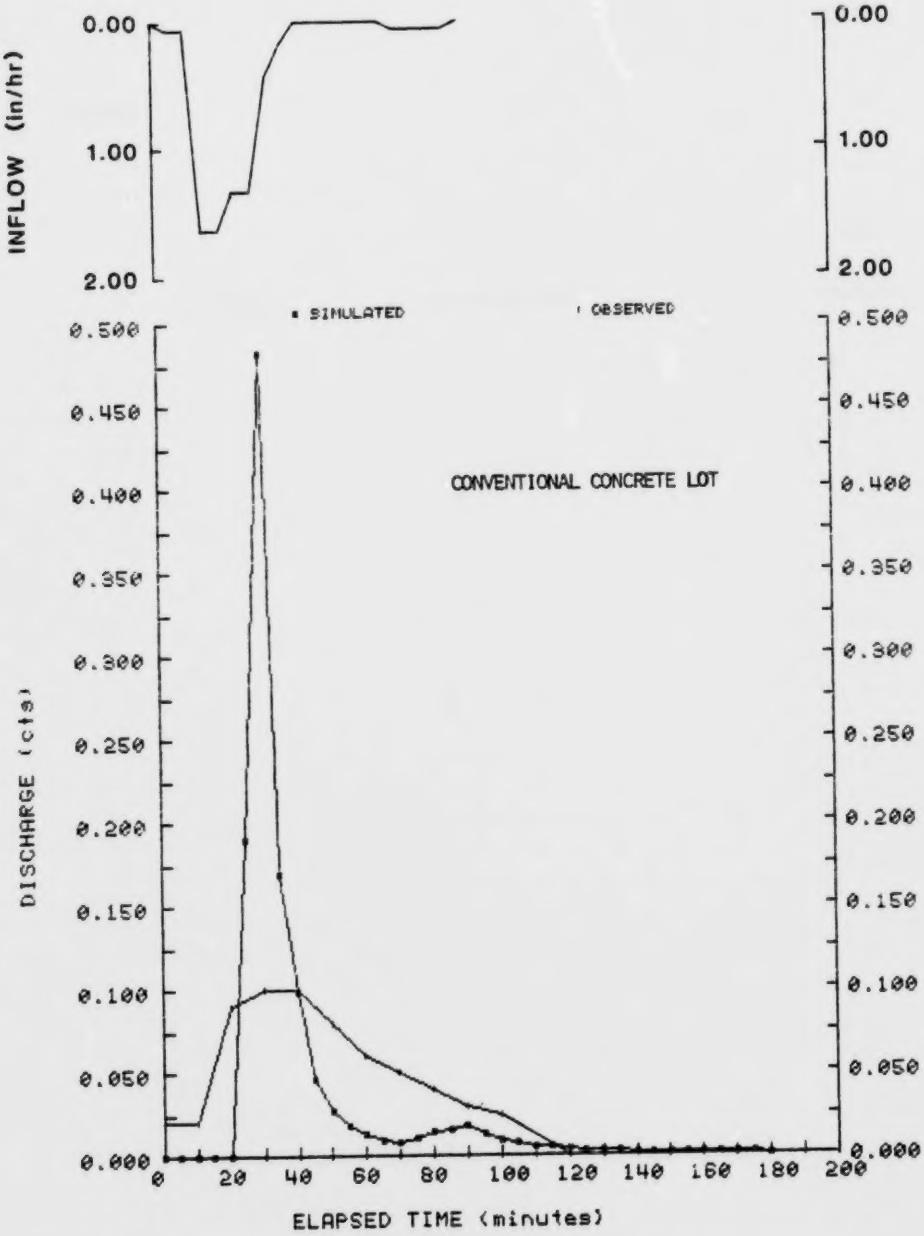


FIG. 43 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 6/3/81.

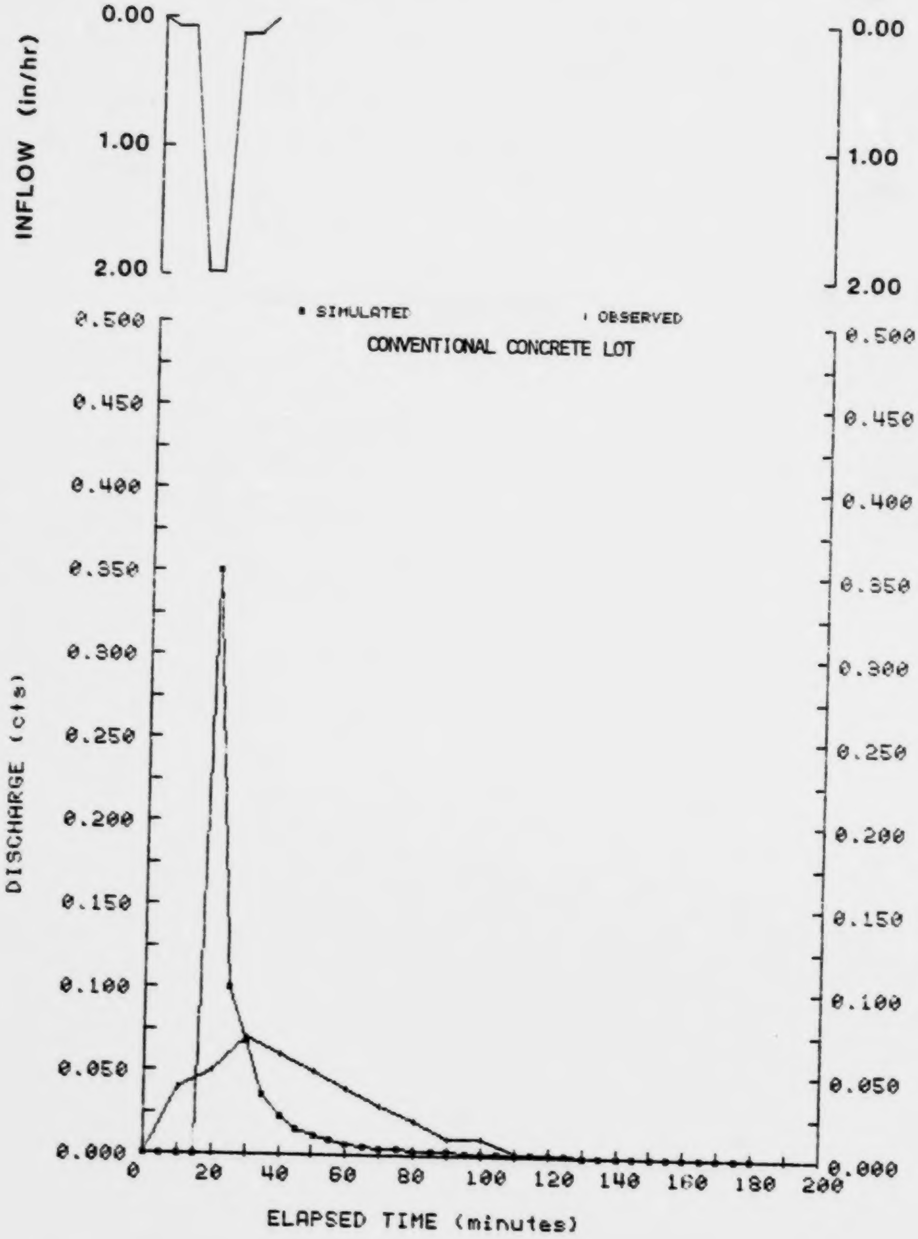


FIG. 44 .SIMULATED VS. OBSERVED HYDROGRAPHS FOR 10/7/81.

The minimum standard error of estimate determined the model which best described the data relationships.

Regression Results

Complete results from the regression analysis for each study lot are presented in Appendix C. A summary is presented in Table 17. The standard error of estimate for Model 4, describing a linear relationship between contaminant load and cumulative discharge, was consistently close to the standard error of Model 3, the power equation, with Model 4 yielding the better fit in 88 percent of the regressions. Overall, the linear relationship between constituent load and flow produced the best fit in 76 percent of the regressions.

Caution should be used in extrapolating the regression results presented here to other pavement facilities. As mentioned earlier, although the data employed in the regression analysis accurately characterized the intraevent water quality characteristics for each study lot, the study pavements may not be representative of other facilities.

TABLE 17

SUMMARY OF REGRESSION ANALYSIS

Pavement Type	Best Model[1]	Coefficients A	Coefficients B
TSS			
Porous Asphalt	4	2.0913	0.0087
Lattice Block	3	0.0097	0.6133
Gravel Trench	3	0.0828	0.7870
Asphalt	4	0.0484	0.0028
Concrete	3	0.0096	0.6189
COD			
Porous Asphalt	3	0.0124	0.6793
Lattice Block	4	0.0119	0.0020
Gravel Trench	4	0.8613	0.0052
Asphalt	4	0.0976	0.0013
Concrete	4	-0.0152	0.0011
TN			
Porous Asphalt	4	0.0005	0.0002
Lattice Block	4	-0.0002	0.0001
Gravel Trench	4	0.0102	0.0001
Asphalt	4*	0.0080	0.0002
Concrete	4*	-0.0228	0.0004

TABLE 17 (Concluded)

Pavement Type	Best Model[1]	Coefficients A	Coefficients B
LEAD			
Porous Asphalt	4	0.0003	0.0000
Lattice Block	4	-0.0014	0.0001
Gravel Trench	4	0.0004	0.0000
Asphalt	1	3.9245	2.0575
Concrete	4	1.5780	0.1178
Zinc			
Porous Asphalt	4	0.0004	0.0000
Lattice Block	4	0.0010	0.0001
Gravel Trench	4	0.0012	0.0000
Asphalt	1	2.6314	1.4962
Concrete	4	-22.986	0.1920

[1] Model 1: $y = A + B (\log_{10}(x))$
Model 2: $y = A \exp(BX)$
Model 3: $y = AX^B$
Model 4: $y = A + BX$

*TKN results (No TN analysis)

SECTION 7

DESIGN METHODOLOGY

OVERVIEW

The liabilities of urban development to indigenous water resources are generally accepted to be manifested in stormwater runoff peaks and event volumes of greater magnitude than in the predeveloped regime, often occurring concomitantly with a degradation of receiving water quality. Some municipalities have addressed these aspects in ordinances requiring the prevention of increased stormwater flows concurrently with the retention of an initial volume of runoff to remove accumulated pollutants. Design criteria of stormwater detention facilities reflect these concerns. The porous pavement design methodology presented below was developed to be flexible enough to satisfy a variety of design criteria.

While the design methodology incorporates the flow governing equations utilized in PORPAV, the two procedures provide distinctly separate functions. PORPAV is a computer simulation program which models detailed intraevent hydraulic characteristics of both pervious and impervious pavement facilities. Used alone, PORPAV can be utilized as a pavement design tool through iterative executions in a trial and error technique. That is, alternative values of the facility's physical characteristics can be modeled for the same inflow condition, and the resulting hydraulic responses compared. The iterative process will continue until specified criteria, e.g. discharge rates, are achieved. As a more direct, albeit less detailed, solution procedure, the design methodology was developed to yield the optimal depth of the pavement facility with a single application. Given the known characteristics of the lot, contributing area, average storm intensity and limiting discharge rate, the design methodology will determine the design depth of the base layer and an estimate of the resulting discharge hydrograph. If a greater degree of detail is desired, PORPAV can be subsequently used to simulate the hydraulic response of the designed pavement facility under a variety of storm conditions. Confidence in the analytical procedures used in the design methodology stems from the success PORPAV demonstrated in simulating hydraulics for a variety of pavement facilities.

A small computer program, PAVDES, was developed to execute the methodology, which is also amenable to solution via computer. For users with a micro-computer or larger available facilities, it is suggested that PAVDES be utilized in place of the design curves for its convenience and greater accuracy. Documentation of the program is provided at the end of this section and in Appendix B.

In the simple use of a pavement facility with base layer storage, as previously shown in Fig. 1, and no drain, or negligible drain to the natural ground, the void volume of the base layer is simply equal to the volume of runoff (on a unit area basis) to be stored or

$$d_b = \text{(Volume to be stored)/porosity of base}$$

However, in instances where there is a non-negligible discharge, the above method would yield a base depth that would be larger than necessary.

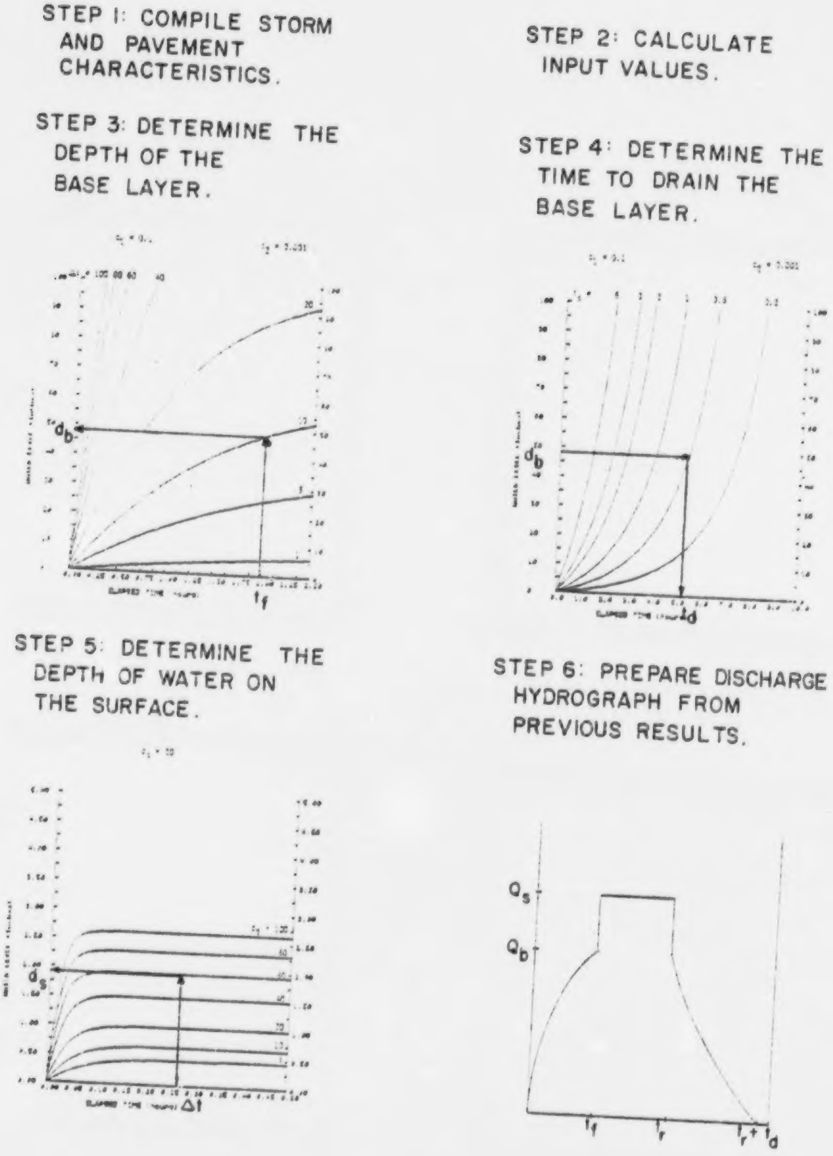
The design methodology produces an optimal base depth for a variety of discharge and volume detention scenarios. Also, a discharge hydrograph, and consequently an estimate of the facility's detention time, may be obtained from the design methodology.

A schematic of the design process is presented in Fig. 45. The design methodology consists of a series of curves which depict the hydraulic characteristics of porous pavement facilities under the influence of various rainfall events and site specific factors. A range of magnitudes of descriptive physical properties for the pavement system are represented in the multiple curves. The initial task is to compile a set of prerequisite information, such as design storm magnitudes, soil properties and discharge and storage constraints. From this data set, necessary input information will be refined. The first group of curves is used to determine the maximum depth of the base layer necessary to retain the design storm flow subject to discharge limitations. The second group of curves provides an estimate of the time required to drain the base layer after the inflow ceases. The final set of curves is used to determine the surface runoff characteristics of the pavement facility. Information from these curves will facilitate the preparation of a discharge hydrograph for the porous pavement system.

Also included in this section are example applications of the methodology. Example worksheets are provided for each example as an aid. Although the water quality data collected and analyzed in this study are limited, a discussion on estimating contaminant loads is provided.

The following design curves are derived from the analytical expressions incorporated in the revised PORPAV. The algorithm was developed to facilitate the design of a porous pavement system without the necessity of computer simulation, and hence, incorporates analytical simplifications, e.g., intra-event inflow rates have been represented by a constant average rate. In general, the design procedures can be employed for any porous pavement system which the model PORPAV can analyze. Appropriate physical and hydraulic characteristics are enumerated below:

- A single, or a set of single, uniformly sloping pavement surfaces.
- The surface is underlain by a base layer of uniform media. This layer may or may not be of uniform thickness and is usually separated from the surface by a permeable filter course.
- Discharge from the base layer can be completely restricted, occur via infiltration to the underlying soil or exit horizontally through seepage to adjacent soils or through a set of collection drain pipes located within the base.
- If a collection drain is present, the base layer cannot contain baffles or other mechanisms which restrict the lateral movement of the water within



STEP 1: COMPILE STORM AND PAVEMENT CHARACTERISTICS.

STEP 2: CALCULATE INPUT VALUES.

STEP 3: DETERMINE THE DEPTH OF THE BASE LAYER.

STEP 4: DETERMINE THE TIME TO DRAIN THE BASE LAYER.

STEP 5: DETERMINE THE DEPTH OF WATER ON THE SURFACE.

STEP 6: PREPARE DISCHARGE HYDROGRAPH FROM PREVIOUS RESULTS.

Figure 45. Schematic of the design methodology.

the base. However, a multiple drain pipe system with these controls may be analyzed as individual units.

- Impermeable seals may or may not be placed along the boundary to prevent leakage to the adjacent soil.

To prepare the design curves it was necessary to establish ranges of the pavement's physical characteristics. The following limitations apply to the design methodology, but do not pertain to PORPAV:

- Pavement length (parallel to slope) of 10 to 1000 feet (3.05 to 305 m).
- Pavement permeability of 0 to 100 inches per hour (0 to 254 cm).
- Base permeability of 0 to 70,000 inches per hour (0 to 177, 800 cm/hr).
- Base depth of 0 to 100 inches (0 to 254 cm).
- Pavement slope of 0 to 0.05 feet per foot (0 to 0.05 m per m).
- Average rainfall intensity of 2 to 10 inches per hour (5.1 to 25.4 cm).
- Minimum soil infiltration rates of 0 to 6 inches per hour (0 to 15.2 cm).
- Contributing watershed-to-pavement area ratio of 1 to 100.

DEVELOPMENT OF THE DESIGN CURVES

The primary hydraulic mechanisms governing transport through the porous pavement are:

1. vertical movement through and between each layer determined by the physical characteristics of the matrix;
2. lateral movement within each layer; and,
3. surface runoff, if the storage capacity of the porous pavement or the surface permeability is exceeded.

The following section describes the analytical components which were derived to describe these mechanisms in a porous pavement system.

Water Depth During Filling

A mass balance approach was used to derive the analytical expression for the depth of water within the base layer during filling. The system was defined as the base layer itself, below the porous surface. The inflow to the system is either the rainfall plus runoff from any contributing areas, or the permeability of the porous surface, whichever is lesser. The outflows from the system consist of infiltration loses and discharge via the collection drain. Mass continuity for this system was written as a nonlinear nonhomogeneous differential equation in the form

$$dd_b/dt = (\Delta i - q_b)/n_b$$

where d_b is the depth of water in the porous base layer (units of length);

i is the average intensity of inflow (length/time);

i_s is the infiltration capacity of the soil (to simplify input requirements, the decay in infiltration rate was neglected) (length/time);

$\Delta i = i - i_s$ (length/time);

q_b is the horizontal discharge from the base per unit area of the porous pavement (length/time); and,

n_b is the porosity of the base media (volume/volume).

The horizontal discharge was derived from Darcy's equation, as discussed in Sec. 4

$$Q_b = (K_b w d_b S_b)/2 + (K_b w d_b^2)/2L$$

expressed on a unit area basis,

$$q_b = c_1 d_b + c_2 d_b^{\,2}$$

where $c_1 = K_b S_b/2L$;

$c_2 = K_b/(2L^2)$;

K_b is the base permeability (length/time);

S_b is the slope of the base layer (length/length);

L is the length of the lot (length); and,

d_b is the depth of water in the base layer (length).

A fourth-order Runge-Kutta numerical method was utilized to solve the differential numerical equation. This method was chosen for its accuracy and stability (20). The family of curves in Appendix D represent solutions to the differential equation describing the water level during the filling of the base layer. The expression Δi was varied from 0 to 100 in/hr (0-250 cm/hr); K_b was varied from near 0 to 70,000 in/hr (0-1780 m/hr); S_b was varied from 0 to 50 percent; L was varied from 10 to 1000 ft (3-300 m), and the porosity of the base layer, n_b was held constant at 25 percent.

For a horizontal base with $c_2 < 0.01$, the term Δi predominates, yielding

$$d_b = (\Delta i \; t)/n_b$$

where t is the elapsed time.

For a horizontal base, the maximum (steady-state) depth is found by solution of

$$dd_b/dt = 0 = (\Delta i - c_2 \, d_{max}^2)/n_b$$

which yields

$$d_{max} = (\Delta i/c_2)^{1/2}$$

which defines the maximum depth water will rise in the system, and therefore, the maximum depth of the base layer.

Time to Drain the Base Layer

When inflow ceases, the base layer will drain via infiltration and/or discharge through collection pipe. The mass balance for this situation is expressed on a unit area basis as

$$dd_b/dt = (i_s - q_b)/n_b$$

The family of curves depicted in Appendix E represent the duration of time necessary to drain the base layer of a given depth after inflow ceases. The infiltration rate was varied from 0.2 to 6 in/hr (0.5-15 cm/hr). The other parameters were varied as described for Appendix D. For a horizontal base with $c_2 < 0.001$ the term i_s predominates, yielding

$$t_d = Dn_b/i_s$$

Surface Depth

Manning's equation was incorporated as the flow governing equation describing surface runoff. On a unit area basis

$$q_s = (1.486\, d_s^{5/3}\, S^{1/2})/(Ln)$$

where q is the surface discharge per unit area of pavement (ft/sec);

d_s is the depth of water on the surface (ft);

S is the slope of the pavement (ft/ft);

L is the length of the pavement (ft), and

n is the Manning's coefficient of roughness for the pavement surface ($ft^{1/6}$/sec).

This was expressed as

$$q_s = c_4(d_s)^{5/3}$$

where $c_4 = (1.486\, S^{1/2})/(Ln)$

For the duration of excess rainfall, infiltration losses (i_s) and discharges from collection drains (q_b) remain constant, as does the inflow (i). Mass continuity for the system during this time was described as

$$dd_s/dt = c_3 - c_4\,(d_s)^{5/3}$$

where $c_3 = i - i_s - q_b$

The family of curves presented in Appendix F represent solutions to the differential equation describing the water levels on the pavement surface after the storage capacity of the parking lot has been exceeded. Values of S ranged from 0.1 to 50 percent, Manning's n ranged from 0.015 to 0.040 $ft^{1/6}$/sec (0.012-0.033 $m^{1/6}$/sec) and L ranged from 10 to 1000 ft (3-300 m).

For $c_4 < 0.01$ the term c_3 predominates, yielding approximately

$$d_s = c_3 t$$

For $c_4 > 20$ the steady state discharge is reached very quickly,

$$dd_s/dt = 0 = c_3 - c_4\,(d_s)^{5/3}$$

$$\text{or}\quad d_{smax} = (c_3/c_4)^{3/5}$$

For this case, the surface discharge, q_s, is equal to

$$q_s = c_4\,(d_{smax})^{5/3} = c_3.$$

PREREQUISITE DATA CRITERIA

In designing a porous pavement system the initial task is to determine the storage and discharge constraints which apply to the facility. Appropriate municipal or watershed ordinances will generally provide the answer. Porous pavement systems can be designed to comply with both stormwater volume control and discharge release rate limitations. In a volume control situation the porous pavement can be designed to capture either an initial portion or the entire volume of the runoff event. The maximum allowable release rate from the porous pavement system may be established from downstream flooding concerns, the watershed master plan or other criteria. If a collection drain is used, a flow control device can be employed to restrict the outflow, allowing an increased detention time.

Presented in Table 18 is a summary of prerequisite information on the contributing area, the design storm and the pavement facility's physical characteristics. The average rainfall intensity, runoff flowrate for any contributing areas (if present) and the duration of overland runoff must be calculated. Municipal drainage manuals generally provide acceptable methods of synthetic hydrograph generation for various frequency storm events.

The infiltration capacity of the soil beneath the porous pavement system is defined as the minimum rate water will percolate into the ground, as determined by on-site percolation tests or literature values. If the porous pavement facility is to take advantage of a favorable infiltration rate, the appropriate value for the underlying soil may be obtained from local Soil Conservation Service general soils information or percolation test data for use in the algorithm. In most instances, an estimate of the surface area allotted to the porous pavement system should be known from space constraints.

The media used for the base layer influences the storage and transport properties of the porous pavement system as a function of porosity and permeability. Specific tests should be conducted or appropriate references should be consulted to obtain these values. Approximate ranges of media permeabilities are presented in Table 19.

TABLE 18

PREREQUISITE DATA CRITERIA

Storm Characteristics	Symbol
Average Rainfall Intensity	i
Average Contributing Area Runoff Flowrate	Q_c
Runoff Duration	t_r
Area of Contributing Area	A_c
Pavement Characteristics	
Surface Permeability	K_p
Surface Slope	S
Base Layer Permeability	K_b
Base Layer Slope	S_b
Base Layer Porosity	n_b
Infiltration Capacity of Soil	i_s
Area of Pavement	A_p
Length of Pavement	L

TABLE 19

PERMEABILITIES OF VARIOUS MEDIA

Media Type	Permeability (inches/hour)
Clean gravels	10,000 - 150,000
Clean sand	500 - 10,000
Clean sand and gravel mixtures	0.1 - 500
Very fine sands	0.010 - 0.1
Silts and clays	0.001 - 0.01

1 in/hr = 2.54 cm/hr

After Peck et al., 1974 (21)

TABLE 20

PERMEABILITIES OF SIMILAR AGGREGATES AS A FUNCTION OF DIAMETER

Diameter (inches)	Permeability (inches/hour)
3/4 - 2	70,000
1/2 - 3/4	50,000
< 1/2	30,000

1 inch = 2.54 cm

After Cedergren, 1967 (22)

With aggregate, the porosity of the base matrix will generally decrease as the aggregate screen size increases due to smaller particles filling the voids between the aggregate. However, the permeability of various diameter similar aggregate generally increases with diameter, as presented in Table 20, due to the decrease in frictional forces.

Variations up to an order of magnitude in these permeabilities are common in field tests. If desired, a range of values can be used throughout the design methodology.

DESIGN PROCEDURES

The design curves presented in Appendices D, E, and F may be used for a variety of porous pavement facilities. These include:

1. complete storm volume capture with unregulated discharge;
2. complete storm capture with a discharge rate limitation;
3. initial storm volume capture with unregulated discharge, and;
4. initial storm volume capture with a discharge rate limitation.

The design procedure of a pavement system with these objectives is addressed below.

For analytical simplicity in PORPAV and in the design methodology it was assumed that the inflow to the pavement system can be represented on a unit area basis, much like uniformly distributed rainfall over the pavement, as

$$i = Q_c/A_p + i_r$$

where i is the inflow to the pavement system per unit area (length/time);

Q_c is the average runoff flowrate from a contributing area (length^3/time);

A_p is the area of the pavement (length^2); and,

i_r is the average rainfall intensity on the pavement (length/time).

The permeability of the porous pavement surface, K_p, or filter course, K_f, is not explicitly included in the algorithm. However, when i becomes equal to or greater than K_p (or K_f), the pavement (or filter) permeability becomes a limiting transport factor. In these instances, K_p (or K_f) is used in place of i throughout the algorithm. A surface outflow quantity equal to the difference between i and K_p (or K_f) is then added to the system discharge.

The presence of hydraulically isolated areas is unavoidable on many pavement surfaces. Quantification of the cumulative capacity of these areas yield marginal estimates at best. During the early portion of a stormwater event these abstractions are generally filled by precipitation and/or runoff. Once filled they have minimal affect on the flow into and through the porous layers. As additional inflow enter these areas an equal amount is displaced onto the pavement. The total volume passing through the base is reduced by an amount equal to the dead storage capacity. On the macroscale of the total pavement area, the effect of dead storage on surface runoff may be evaluated as an apparent decrease in the depth of water on the pavement available to flow offsite. This mechanically simple, yet sufficiently accurate, treatment is incorporated in PORPAV. No correction is required for surface depth or runoff in the design procedures, while the total volume passing through the base must be adjusted.

Design of a Porous Pavement System on a Volume Basis

A common objective in the design of a porous pavement facility is to capture and detain a predetermined inflow volume. For a facility with subsurface discharge during the event, the void volume of the system will be less than the volume of inflow to be captured. If the facility is to capture the entire volume without surface runoff, the peak subsurface discharge will occur at the time the base layer becomes filled, t_f. Depending on the rainfall intensity and base layer characteristics, this will occur at or before inflow ceases, t_r. The total system discharge will consist of the collection drain discharge and/or the infiltration losses, which will continue until the base layer storage is drained. The resulting outflow hydrograph will resemble the one presented in Fig. 46(a) for the case when $t_f = t_r$ or Fig. 46(b) if $t_f < t_r$. If steady state has been reached, the peak discharge from this system will equal the difference of the average inflow and any infiltration loss.

The same principles apply in a system designed to capture an initial volume of storm flow and bypass the remainder. The pavement system accepts the total inflow until the storage capacity is exceeded, at which time surface runoff begins, and the pavement system becomes a flow-limited facility, constrained by the sum of the lateral flux of effluent from the collection drain and the vertical soil infiltration losses. Inflow subsequent to the initial volume will be routed directly across the pavement surface, changed in magnitude by the soil infiltration and collection drain losses. The total outflow from this system is the summation of surface and collection drain discharges, as depicted in Fig. 46(c).

In instances where zero discharge is mandated for specified duration, a controlled release may be employed. The only loss from the system during this time would be soil infiltration, if present. The porous system in this case would be designed so that the void volume is equal to the predetermined volume of the stormwater runoff.

Watershed ordinances may specify a minimum detention period for stormwater runoff from developed areas. The theoretical duration of detention is computed as the elapsed time between the center of mass of the inflow hydrograph and the center of mass of the discharge hydrograph. The design procedure provides enough information on the outflow hydrograph for the user to compute an estimate of the theoretical detention time provided by the pavement facility.

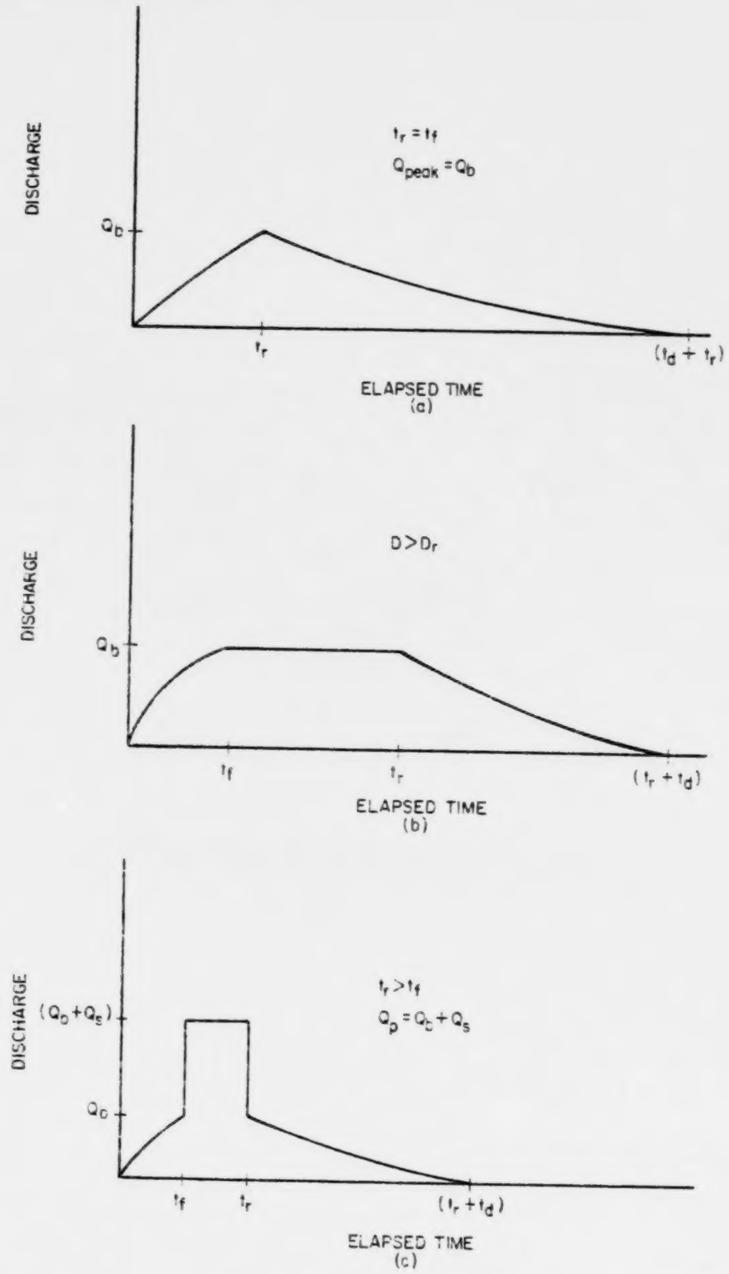


Figure 46. Discharge hydrographs for various porous pavement facilities.

Design Procedure for the Capture of the Entire Storm Runoff Volume

A worksheet for the design methodology is presented in Table 21, including the units of the various parameters.

1. Determine the average inflow rate, Q_c (cfs), the duration of runoff, t_r (hour) and the average rainfall intensity on the pavement, i_r (in/hr), during the runoff duration.

2. Compile the physical characteristics of the pavement lot:
   a. Determine the soil infiltration capacity, i_s (in/hr);
   b. Determine the base permeability K_b(in/hr), porosity, n_b (ft^3/ft^3), and slope, S_b (ft/ft); and,
   c. Determine the length and area of the porous system, L (ft) and A_p (ft^2).

3. Determine the depth of the base layer, D:
   a. Calculate the inflow rate,

   $$i = 43200\ (Q_c/A_p) + i_r$$

   b. Calculate the difference between the inflow rate and the infiltration rate

   $$\Delta i = i - i_s$$

   c. Calculate $c_1 = K_b S_b / 24L$;
   d. Calculate $c_2 = K_b/(288\ L^2)$;
   e. If t_r is less than or equal to 2.5 hours, enter Appendix D (interpolate from the appropriate bracket of c_1 and c_2) at t_r to determine D. For a horizontal base with a small c_1, D is approximately equal to $(\Delta i t_r)/n_b$.

   If t_r is greater than 2.5 hours, it is assumed that steady state has been reached and D is calculated by the following iterative technique:

   i. First choice of D is $(\Delta i/c_2)^{1/2}$
   ii. New D is $((\Delta i - c_1 D)/c_2)^{1/2}$
   iii. Repeat step ii. until $(D_{old} - D_{new}) < 1.0$

4. Determine the discharge hydrograph characteristics
   a. The peak discharge from the collection drain, Q_b (cfs), will occur at or before t_r, as presented in Appendix D. Q_b is determined from

   $$Q_b = (c_1 D + c_2 D^2)\ A_p/43200$$

TABLE 21

WORKSHEET FOR COMPLETE VOLUME CAPTURE WITH UNINTERRUPTED DISCHARGE

Storm Characteristics

i_r (in/hr) =

Q_c (cfs) =

t_r (hr) =

Pavement Characteristics

K_p (in/hr) =

K_b (in/hr) =

L (ft) =

A_p (ft^2) =

S_b (ft/ft) =

n_b (ft^3/ft^3) =

i_s (in/hr) =

Design Procedures

$i = 43200\ Q_c/A_p + i_r$ =

$\Delta i = i - i_s$ =

$c_1 = K_b S_b/24L$ =

$c_2 = K_b/288L^2$ =

D (from Appendix D; if $t_r > 2.5$ hr, use interative technique) =

First choice of $D = (\Delta i/c_2)^{1/2}$ =

new $D = ((\Delta i - c_1 D)/c_2)^{1/2}$; repeat until within 1 inch

t_d (from Appendix E) =

$q_b = c_1 D + c_2 D^2$ =

$Q_b = q_b A_p/43200$ =

$V_b = (it_r - i_s\ (t_r + t_d))Ap/12$ =

b. Determine the time to drain, t_d (hours), from Appendix E. Enter Appendix E (interpolate from the appropriate bracket of c_1 and c_2) with D and i_s to find t_d.

c. Calculate the total volume of discharge, V_b (ft^3) from

$$V_b = (i\ t_r - i_s\ (t_r + t_d))A_p/12$$

Design Procedure for the Capture of an Initial Portion of the Storm Runoff Volume

A worksheet for the design methodology is presented in Table 22, including the units of the various parameters.

1. Determine the inflow characteristics, i_r, Q_c and t_r. Determine the contributing area A_c and the initial stormwater volume to be detained by the pavement system, v, in inches.

2. Compile the physical characteristics of the pavement:
   a. Determine the soil infiltration capacity, i_s.
   b. Determine the base permeability, K_b, porosity, n_b and slope, S_b.
   c. Determine the area and slope of the pavement, A_p and S.
   d. Determine the Manning's coefficient, n, for the pavement.
   e. Calculate the volume to be detained, normalized to the pavement area,

$$v_p = v(A_c + A_p)/A_p.$$

3. Determine the depth of the base layer, D:
   a. Calculate the inflow rate, i

$$i = 43200\ (Q_c/A_p) + i_r$$

   b. Calculate the difference between the inflow and infiltration rate, Δi

$$\Delta i = i - i_s$$

   c. The time required to capture the initial volume is

$$t_f = v_p/i$$

   d. The depth of the base layer depends on the operating policy enacted. For a zero discharge policy,

$$D = t_f\ \Delta i/n_b$$

   The corresponding time to drain the base is

$$t_d = Dn_b/i_s$$

TABLE 22

WORKSHEET FOR INITIAL VOLUME CAPTURE WITH UNINTERRUPTED DISCHARGE

Storm Characteristics

i_r (in/hr) =
Q_c (cfs) =
t_r (hr) =
v (in) =
A_c (ft^2) =

Pavement Characteristics

K_p (in/hr) =
K_b (in/hr) =
L (ft) =
A_p (ft^2) =
S_b (ft/ft) =

S (ft/ft) =
n_b (ft^3/ft^3) =
i_s (in/hr) =
n =

$v_p = v(A_c + A_p)/A_p$ =
$i = 43200\ Q_c/A_p + i_r$ =
$\Delta i = i - i_s$ =
$c_1 = K_b S_b/24L$ =
$c_2 = K_b/288L^2$ =
$t_f = v_p/i$ =
D (from Appendix D) =
$\Delta_t = t_r - t_f$ =
$q_b = c_1 D + c_2 D^2$ =
$Q_b = q_b\ A_p/43200$ =
$c_3 = \Delta i - q_b$ =
d_s (from Appendix F if not steady state) $= (c_3/c_4)^{3/5}$ =
$q_s = c_4(d_s)^{5/3}$ =
$Q_s = q_s A_p/43200$ =
$Q_p = Q_b + Q_s$ =
t_d (from Appendix E) =
$V_b = (\Delta i t_f - i_s t_d)A_p/12$ =

For a nonzero discharge, D is found from Appendix D, entering the horizontal axis at t_f. The corresponding time to drain the base is found from Appendix E.

4. Determine the discharge hydrograph characteristics
   a. $c_1 = K_b S_b/24L$

      $c_2 = K_b/(288L^2)$

      Calculate the base discharge, q_b, from

      $q_b = c_1 D + c_2 D^2$

   b. Determine the maximum surface runoff.
      i. Calculate $\Delta t = t_r - t_f$
      ii. Calculate $c_3 = \Delta i - q_b$
      iii. Calculate $c_4 = (1021\, S^{1/2})/(nL)$
      iv. Enter Appendix D with Δt and appropriate ranges of c_3 and c_4 to find d_s.
      v. Calculate the surface discharge, q_s, from

$$q_s = c_4 (d_s)^{5/3}$$

      After steady state is reached, $q_s = c_3$.

   c. Peak discharge (on a unit area basis) = $q_b + q_s$

      After steady state is reached, the peak discharge is equal to Δi.

   d. Determine the runoff volume
      i. For a zero discharge policy,

$$V_b = 0$$

      ii. For nonzero discharge,

$$V_b = (\Delta i t_f - i_s t_d)\, A_p/12$$

Design of a Porous Pavement System With a Discharge Limitation

As a measure of decreasing downstream flooding risks, watershed ordinances may limit the discharge rate from stormwater control facilities. For a given storm event, a design incorporating this limitation can utilize a collection system (e.g., pipe) with a discharge limiting mechanism and determine the remaining dimensions of the system. Several combinations of initial or complete volume capture, limited release rates and detention time constraints may be handled by the design curves.

Design Procedure for a Discharge-limited System

Worksheets for the design methodology are presented in Table 23 for a complete volume capture with a limited discharge, and in Table 24 for an initial volume capture

TABLE 23

WORKSHEET FOR COMPLETE VOLUME CAPTURE WITH LIMITED RELEASE RATE

Storm Characteristics

i_r (in/hr) =

Q_c (cfs) =

t_r (hr) =

Pavement Characteristics

K_p (in/hr) =

K_b (in/hr) =

L (ft) =

A_p (ft^2) =

S_b (ft/ft) =

S (ft/ft) =

n_b (ft^3/ft^3) =

i_s (in/hr) =

Q_p (cfs) =

Design Procedures

$i = 43200\ Q_c/A_p + i_r$ =

$\Delta i = i - i_s$ =

$q_p = 43200\ Q_p/A_p$ =

$c_1 = K_b S_b/24L$ =

$c_2 = K_b/288L^2$ =

apparent depth, D'
(iterative technique)

1st choice $D' = (q_p/c_2)^{1/2}$ =

$\Delta D = D' - ((q_p - c_1 D')/c_2)^{1/2}$ =

new choice of D' is $D' - (\Delta D/2)$; repeat until $\Delta D < 1$

t_f' (from Appendix D) =

$\Delta_t = t_r - t_f'$ =

$D = \Delta t\ (\Delta i - q_p)/n_b + D'$ =

t_d' (from Appendix E) =

$t_d = t_d' + (D - D')n_b/(q_p + i_s)$ =

$V_b = (\Delta i t_r - t_d i_s)\ Ap/12$ =

TABLE 24

WORKSHEET FOR INITIAL VOLUME CAPTURE WITH ZERO DISCHARGE

Storm Characteristics		Pavement Characteristics			
i_r (in/hr)	=	K_p (in/hr)	=	S (ft/ft)	=
Q_c (cfs)	=	K_b (in/hr)	=	n_b (ft^3/ft^3)	=
t_r (hr)	=	L (ft)	=	i_s (in/hr)	=
v (in)	=	A_p (ft^2)	=	n	=
A_c (ft^2)	=	S_b (ft/ft)	=		

$v_p = v(A_c + A_p)/A_p$ =

$i = 43200\ Q_c/A_p + i_r$ =

$\Delta i = i - i_s$ =

$c_1 = K_b S_b/24L$ =

$c_2 = K_b/288L^2$ =

$t_f = v_p/i$ =

$D = t_f\ \Delta i/n_b$ =

$\Delta_t = t_r - t_f$ =

$c_3 = \Delta i$ =

$c_4 = 1021S^{1/2}/(nL)$ =

$t_d = Dn_b/i_s$ =

$c_4 = 1021S^{1/2}/(nL)$ =

d_s (from Appendix F if not steady state) $= (c_3/c_4)^{3/5}$ =

$q_s = c_4(d_s)^{5/3}$ =

$Q_p = q_s A_p/43200$ =

$V_b = 0$ =

with zero discharge. The procedure for a complete volume capture with a limited discharge is presented below.

1. Determine the inflow hydrograph characteristics Q_c and t_r, the average rainfall intensity on the pavement, i_r, during the runoff duration and the maximum discharge, Q_p.

2. Compile the physical characteristics of the pavement lot:
   a. Determine the soil infiltration capacity, i_s;
   b. Determine the base permeability K_b, porosity, n_b, and slope, S_b; and,
   c. Determine the length, slope and area of the porous system, L, S and A_p.
   d. Determine the maximum pipe capacity, q_p, normalized to the pavement area

$$q_p = 43200Q_p/A_p$$

3. Determine the depth of the base layer, D:
   a. Calculate the inflow rate,

$$i = Q_c/A_p + i_r$$

   b. Calculate the difference between the inflow rate and the infiltration rate

$$\Delta i = i - i_s$$

   c. Calculate $c_1 = K_b S_b/(24L)$;
   d. Calculate $c_2 = K_b/(288\ L^2)$;
   e. Determine the apparent depth, D', using the following iterative technique.
      i. First choice of D' is

$$D' = (q_p/c_2)^{1/2}$$

      ii. $\Delta D = D' - ((q_p - c_1 D')/c_2)^{1/2}$

      iii. New choice of D' is $(D' - \Delta D/2)$
      Repeat step ii. until $\Delta D < 1.0$.

   f. Determine the time to fill D' from Appendix D.
   g. Calculate $\Delta t = t_r - t_f$
   h. $D = \Delta t\,(\Delta i - q_p)/n_b + D'$

4. Determine the discharge hydrograph characteristics.
   a. Enter Appendix E with D' to find apparent time to drain t_d'.
   b. Calculate time to drain, t_d,

$$t_d = t_d' + (D-D')n_b/(q_p + i_s)$$

c. The total volume detained is calculated the same as before,

$$V_b = (\Delta i\ t_r - i_s\ t_d)\ A_p/12$$

EXAMPLE APPLICATIONS

Basic example applications of the design manual are presented below to clarify procedural mechanics and to demonstrate operational characteristics of the resulting porous pavement systems. The examples cover a range of systems which have been previously discussed.

For most of these examples, a 6-hr, 7-in (17.8 cm) design storm was chosen for a 1-ac (0.4-ha) porous pavement facility with a 4-ac (1.6-ha) contributing area, having a runoff to rainfall ratio of 0.80. The pavement permeability was 50 in/hr (127 cm/hr) while the base layer permeability was 15,000 in/hr (38,100 cm/hr) with a porosity of 25 percent. The lot was 208 ft (63 m) on each side and had a 1 percent slope. The natural soil infiltration capacity was 0.5 in/hr (1.3 cm/hr).

Table 25 presents an example of complete storm capture with unregulated discharge. The depth of the base layer was determined to be 49 in (125 cm), having a maximum base discharge of 4.4 cfs (124.6 l/s), occurring at the end of the 6-hr event. For comparison, if the base depth was determined by volume considerations alone, neglecting the base discharge, the design depth would be

$$d_b = (7\text{ in}) * (5\text{ ac}/1\text{ ac})/.25 = 140\text{ inches } (356\text{ cm})$$

The base layer discharged 78,756 ft^3 (2,230 m^3) over the 9-hr drainage duration. The outflow hydrograph resembles the one presented in Fig. 46(a).

An example of a limited discharge rate is presented in Table 26. The same storm and pavement characteristics were used, in conjunction with a 1 cfs (28.3 l/s) discharge limitation. For the entire volume capture, the base layer depth was determined to be 97 in (246 cm) and provides an 11.4 hr drainage time. Infiltration losses accounted for almost 30,000 ft^3 (850 m^3) more volume than in the complete event capture due to the increased drainage time. The discharge hydrograph resembles Fig. 46(b).

Table 27 details the procedures to determine the pavement performance for the capture of the first half-inch (1.3 cm) of runoff. With similar storm and pavement characteristics as before, the new objective decreases the base layer depth to just over 7 in (17.8 cm). A peak surface runoff of 4.08 in/hr (10.4 cm/hr) (4.11 cfs or 116.4 l/s) results from the pavement facility, similar to the hydrograph in Fig. 46(c).

An example of an initial volume capture with zero discharge is presented in Table 28. The base layer depth was increased to 9 in (22.9 cm) and the surface runoff was increased to 4.4 cfs (124.6 l/s) by the discharge restriction.

Tables 29 and 30 detail the procedures for an initial volume capture with an unregulated discharge. In this example a filter course with a permeability of 15 in/hr (38.1 cm/hr) is used to provide a thin base for the porous pavement. The calculations in Table 29 document the necessity to use a filter course with a greater permeability.

TABLE 25

EXAMPLE APPLICATION FOR COMPLETE VOLUME CAPTURE WITH UNINTERRUPTED DISCHARGE

Storm Characteristics

i_r (in/hr) = 1.167

Q_c (cfs) = 3.73

t_r (hr) = 6

Pavement Characteristics

K_p (in/hr) = 50

K_b (in/hr) = 15,000

L (ft) = 208

A_p (ft^2) = 43560

S (ft/ft) = 0.010

n_b (ft^3/ft^3) = 0.25

i_s (in/hr) = 0.5

Design Procedures

$i = 43200\ Q_c/A_p + i_r$ = 4.866 in/hr

$\Delta i = i - i_s$ = 4.366 in/hr

$c_1 = K_b S_b/24L$ = 0.030

$c_2 = K_b/288L^2$ = 0.0012

D (from Appendix D; if $t_r > 2.5$ hr, use interative technique) =

First choice of $D = (\Delta i/c_2)^{½}$ = 60.43 in

new $D = ((\Delta i - c_1 D)/c_2)^{½}$; repeat until within 1 inch

46.12; 49.85; 48.91; use D = 49 in

t_d (from Appendix E) = 10.5 for $c_1 = 0.01$; 5.5 for $c_1 = 0.1$;

t_d = 9 hr

$q_b = c_1 D + c_2 D^2$ = 4.351 in/hr

$Q_b = q_b A_p/43200$ = 4.387 cfs

$V_b = (i t_r - i_s (t_r + t_d))Ap/12$ = 78,756 ft^3

TABLE 26

EXAMPLE APPLICATION FOR COMPLETE VOLUME CAPTURE WITH LIMITED RELEASE RATE

Storm Characteristics

i_r (in/hr) = 1.167

Q_c (cfs) = 3.73

t_r (hr) = 6

Pavement Characteristics

K_p (in/hr) = 50

K_b (in/hr) = 15,000

L (ft) = 208

A_p (ft^2) = 43560

S (ft/ft) = 0.010

n_b (ft^3/ft^3) = 0.25

i_s (in/hr) = 0.5

Q_p (cfs) = 1

Design Procedures

$i = 43200\ Q_c/A_p + i_r$ = 4.865 in/hr

$\Delta i = i - i_s$ = 4.365 in/hr

$q_p = 43200\ Q_p/A_p$ = 0.992 in/hr

$c_1 = K_b S_b/24L$ = 0.030

$c_2 = K_b/288L^2$ = 0.0012

apparent depth, D'
(iterative technique)

1st choice $D' = (q_p/c_2)^{1/2}$ = 28.75

$\Delta D = D' - ((q_p - c_1 D')/C_2)^{1/2}$ = 10.39

new choice of D' is D' - (ΔD/2); repeat until $\Delta D < 1$

19.57, $\Delta D = 1.2$; 18.97, $\Delta D = 0.20$ use D = 19 in

t_f' (from Appendix D) = 0.25 hr

$\Delta_t = t_r - t_f'$ = 5.75 hr

$D = \Delta t\ (\Delta i - q_p)/n_b + D'$ = 96.58 in

t_d' (from Appendix E) = $c_1 = 0.01$ t_d = 13./5 hr; $c_1 = 0.1$ t_d = 6.4 hr; t_d = 11.4 hr

$t_d = t_d' + (D - D')n_b/(q_p + i_s)$ = 24.4 hr

$V_b = (\Delta i t_r - t_d i_s)\ Ap/12$ = 50,785 ft^3

TABLE 27

EXAMPLE APPLICATION FOR INITIAL VOLUME CAPTURE WITH UNINTERRUPTED DISCHARGE

Storm Characteristics		Pavement Characteristics			
i_r (in/hr)	= 1.167	K_p (in/hr)	= 50	S (ft/ft)	= 0.010
Q_c (cfs)	= 3.73	K_b (in/hr)	= 15000	n_b (ft^3/ft^3)	= 0.25
t_r (hr)	= 6	L (ft)	= 208	i_s (in/hr)	= 0.5
v (in)	= 0.5	A_p (ft^2)	= 43560	n	= 0.015
A_c (ft^2)	= 174,240	S_b (ft/ft)	= 0.010		

$v_p = v(A_c + A_p)/A_p$ = 2.5 in

$i = 43200\ Q_c/A_p + i_r$ = 4.865 in/hr

$\Delta i = i - i_s$ = 4.365 in/hr

$c_1 = K_b S_b / 24L$ = 0.030

$c_2 = K_b / 288L^2$ = 0.0012

$t_f = v_p / i$ = 0.514 hr

D = (from Appendix D) = $c_1 = 0.01$, D = 7.5; $c_1 = 0.1$, D = 7.0; D = 7.35 in

$\Delta_t = t_r - t_f$ = 5.486 hr

$q_b = c_1 D + c_2 D^2$ = 0.285 in/hr

$c_3 = \Delta i - q_b$ = 4.08 in/hr

$c_4 = 1021\ S^{1/2}/(nL)$ = 32.74

d_s (from Appendix F if not steady state) $= (c_3/c_4)^{3/5}$ = 0.287 in

$q_s = c_4 (d_s)^{5/3}$ = 4.08 in/hr

t_d = (from Appendix E) = $c_1 = 0.01$, $t_d = 3.0$ hr; $c_1 = 0.1$, $t_d = 2.0$ hr; $t_d = 2.7$ hr

$V_b = (\Delta i t_f - i_s t_d) A_p / 12$ = 3,244 ft^3

TABLE 28

EXAMPLE APPLICATION FOR INITIAL VOLUME CAPTURE WITH ZERO DISCHARGE

Storm Characteristics		Pavement Characteristics			
i_r (in/hr)	= 1.167	K_p (in/hr)	= 50	S (ft/ft)	= 0.010
Q_c (cfs)	= 3.73	K_b (in/hr)	= 15,000	n_b (ft^3/ft^3)	= 0.25
t_r (hr)	= 6	L (ft)	= 208	i_s (in/hr)	= 0.5
v (in)	= 0.5	A_p (ft^2)	= 43,560	n	= 0.015
A_c (ft^2)	= 174,240	S_b (ft/ft)	= 0.010		

$v_p = v(A_c + A_p)/A_p$	= 2.5 in
$i = 43200\ Q_c/A_p + i_r$	= 4.865 in/hr
$\Delta i = i - i_s$	= 4.365 in/hr
$c_1 = K_b S_b/24L$	= 0.030
$c_2 = K_b/288L^2$	= 0.0012
$t_f = v_p/i$	= 0.514 hr
$D = t_f\ \Delta i/n_b$	= 8.97 in
$\Delta_t = t_r - t_f$	= 5.486 hr
$c_3 = \Delta i$	= 4.365 in/hr
$t_d = Dn_b/i_s$	= 4.485 hr
$c_4 = 1021\ S^{1/2}/(nL)$	= 32.72
d_s (from Appendix F if not steady state) $= (c_3/c_4)^{3/5}$	= 0.299 in
$q_s = c_4\ (d_s)^{5/3}$	= 4.365 in/hr
$Q_p = q_s A_p/43200$	= 4.4 cfs
$V_b = 0$	= 0 ft^3

TABLE 29

EXAMPLE APPLICATION FOR INITIAL VOLUME CAPTURE WITH UNINTERRUPTED DISCHARGE

Storm Characteristics		Pavement Characteristics			
i_r (in/hr)	= 1.167	K_p (in/hr)	= 10,000	S (ft/ft)	= 0.04
Q_c (cfs)	= 0.933	K_b (in/hr)	= 15,000	n_b (ft^3/ft^3)	= 0.25
t_r (hr)	= 6	L (ft)	= 208	i_s (in/hr)	= 0.5
v (in)	= 0.5	A_p (ft^2)	= 2080	n	= 0.04
A_c (ft^2)	= 43,560	S_b (ft/ft)	= 0.04	K_f (in/hr)	= 15

$v_p = v(A_c + A_p)/A_p$ = 10.971 in

$i = 43200\, Q_c/A_p + i_r$ = 20.55 in/hr which is > K_f; since this implies the initial storm volume cannot be completely detained, a new filter cloth must be chosen with a greater permeability.

$\Delta i = i - i_s$ =

$c_1 = K_b S_b/24L$ =

$c_2 = K_b/288L^2$ =

$t_f = v_p/i$ =

$D = t_f\, \Delta i/n_b$ =

$\Delta_t = t_r - t_f$ =

$c_3 = \Delta i$ =

$t_d = Dn_b/i_s$ =

$c_4 = 1021\, S^{1/2}/(nL)$ =

d_s (from Appendix F if not steady state) $= (c_3/c_4)^{3/5}$ =

$q_s = c_4\, (d_s)^{5/3}$ =

$V_b = 0$ =

TABLE 30

EXAMPLE APPLICATION FOR INITIAL VOLUME CAPTURE WITH UNINTERRUPTED DISCHARGE

Storm Characteristics		Pavement Characteristics			
i_r (in/hr)	= 1.167	K_p (in/hr)	= 10,000	S (ft/ft)	= 0.04
Q_c (cfs)	= 0.933	K_b (in/hr)	= 15,000	n_b (ft^3/ft^3)	= 0.25
t_r (hr)	= 6	L (ft)	= 208	i_s (in/hr)	= 0.5
v (in)	= 0.5	A_p (ft^2)	= 2080	n	= 0.04
A_c (ft^2)	= 43,560	S_b (ft/ft)	= 0.04	K_f (in/hr)	= 25

$v_p = v(A_c + A_p)/A_p$ = 10.971 in

$i = 43200\ Q_c/A_p + i_r$ = 20.55 in/hr

$\Delta i = i - i_s$ = 20.05 in/hr

$c_1 = K_b S_b/24L$ = 0.120

$c_2 = K_b/288L^2$ = 0.0012

$t_f = v_p/i$ = 0.534 hr

D = (from Appendix D) = 37 in

$\Delta t = t_r - t_f$ = 5.466 hr

$q_b = c_1 D + c_2 D^2$ = 6.083 in/hr

$Q_b = q_b Ap/43200$ = 0.293 cfs

$c_3 = \Delta i - q_b$ = 13.97 in/hr

$c_4 = 1021\ S^{1/2}/(nL)$ = 24.54

d_s (from Appendix F if not steady state) $= (c_3/c_4)^{3/5}$ = 0.713 in

$q_s = c_4\ (d_1)^{5/3}$ = 13.97 in/hr

$Q_s = q_s A_p/43200$ = 0.673 cfs

$Q_p = Q_s + P_b$ = 0.9655 cfs

t_d = (from Appendix E) = 3.25 hr

$V_b = (\Delta i t_f - i_s t_d)A_p/12$ = 1574 ft^3

Table 30 presents the results of using a filter course with a permeability of 25 in/hr (63.5 cm/hr).

Design of a Porous Pavement Facility Using PAVDES

PAVDES is a computer program which was developed to execute the design methodology. Its use is recommended over the design curves for convenience and accuracy. The input variables and format are summarized in Table 31. The depth of the base layer, the time to fill the base layer, the maximum base discharge, the time to drain the base layer, the total volume discharged from the base, the maximum surface depth, the maximum surface discharge and the total (base plus surface) discharge hydrograph are printed as output. PAVDES can be run with a variety of input values to compare alternative designs and discharge or volume restrictions. PORPAV can be utilized to estimate the hydraulic response of the facility designed in PAVDES to a variety of stormwater events. A sample execution of PAVDES is displayed in Table 32.

Estimation of Water Quality

The hydraulic performance of porous pavement facilities may be characterized by the design methodology presented herein. However, contaminant removal within porous pavement systems was not described due to a lack of water quality data from a variety of pavement types under a range of storm event conditions. Relationships between constituent concentrations and discharge were not consistent enough to be described by regression analysis. The engineer or planner wishing to incorporate water quality impacts of a porous pavement facility may utilize literature values, collect site specific data or use the regression equations developed in this study for preliminary assessment.

TABLE 31

INPUT VARIABLES FOR PAVDES

Storm Characteristics	Symbol
Average rainfall intensity (in/hr)	I_r
Average runoff flowrate (cfs)	Q_c
Duration of rainfall and subsequent runoff (hours)	T_r
Area of contributing area (ft^2)	A_c
Volume (on a unit area basis) to be contained (in)	v
Pavement Characteristics	
Surface permeability (in/hr)	K_p
Base permeability (in/hr)	K_b
Pavement length (ft)	L
Pavement area (ft^2)	A_p
Surface slope (ft/ft)	S
Base slope (ft/ft)	S_b
Base porosity (ft^3/ft^3)	n_b
Soil infiltration capacity (in/hr)	i_s
Manning's n for surface (ft$^{1/6}$/s)	n
Filter course permeability (in/hr)	k_f
Maximum allowable discharge (cfs)	Q_p

INPUT FORMAT

Data Line	Variables
1.	I_r, Q_c, T_r, A_c, v
2.	K_p, K_b, L, A_p, S, S_b, n_b, i_s, n, k_f, Q_p

TABLE 32. SAMPLE EXECUTION OF PAVDES.

```
STORM AND PAVEMENT CHARACTERISTICS

AVERAGE RAINFALL INTENSITY (IN/HR)          1.167
AVERAGE RUNOFF RATE (CFS)                   3.730
RAINFALL DURATION (HOURS)                   6.000
CONTRIBUTING AREA (SQ. FT.)            174240.000
VOLUME TO DETAIN (INCHES)                 100.000
PAVEMENT PERMEABILITY (IN/HR)              50.000
BASE PERMEABILITY (IN/HR)               15000.000
PAVEMENT LENGTH (FT)                      208.000
PAVEMENT AREA (SQ FT)                   43560.000
SURFACE SLOPE (FT/FT)                       0.010
BASE LAYER SLOPE (FT/FT)                    0.010
BASE POROSITY (CU FT/CU FT)                 0.250
SOIL INFILTRATION RATE (IN/HR)              0.500
MANNINGS N (FT1/6/SEC)                      0.020
FILTER CLOTH PERMEABILITY (IN/HR)          50.000
MAXIMUM ALLOWABLE DISCHARGE (CFS)          10.000


DEPTH OF THE BASE LAYER IS 46.7  INCHES.
THE TIME TO FILL THE BASE LAYER IS  6.00  HOURS.
THE MAXIMUM BASE DISCHARGE IS   4.067  CFS.
THE TIME TO DRAIN THE BASE LAYER IS  8.28  HOURS.
THE TOTAL VOLUME DISCHARGED FROM THE BASE IS     80066.  CUBIC FT
THE MAXIMUM SURFACE DEPTH IS  0.00  INCHES.
THE MAXIMUM SURFACE DISCHARGE IS  0.000  CFS.
```

TABLE 32. (Concluded)

TIME	DEPTH IN BASE	DISCHARGE
0.00000	0.00000	0.00000
0.24000	4.12509	0.14444
0.48000	8.09509	0.32213
0.72000	11.88097	0.52693
0.96000	15.45985	0.75227
1.20000	18.81519	0.99154
1.44000	21.93668	1.23847
1.68000	24.81973	1.48738
1.92000	27.46488	1.73335
2.15999	29.87696	1.97234
2.39999	32.06426	2.20117
2.63999	34.03773	2.41751
2.87998	35.81014	2.61980
3.11998	37.39548	2.80715
3.35998	38.80830	2.97921
3.59997	40.06324	3.13608
3.83997	41.17474	3.27818
4.07997	42.15665	3.40619
4.31996	43.02209	3.52094
4.55995	43.78337	3.62336
4.79994	44.45184	3.71446
5.03994	45.03790	3.79521
5.27993	45.55103	3.86658
5.51992	45.99975	3.92952
5.75991	46.39175	3.98490
5.99990	46.73389	4.03354
6.23990	42.60881	3.46591
6.47989	38.98693	3.00131
6.71988	35.77899	2.61618
6.95987	32.91570	2.29336
7.19986	30.34245	2.02007
7.43986	28.01559	1.78668
7.67985	25.89980	1.58578
7.91984	23.96621	1.41160
8.15983	22.19099	1.25962
8.39981	20.55429	1.12622
8.63979	19.03942	1.00849
8.87977	17.63230	0.90409
9.11976	16.32088	0.81108
9.35974	15.09489	0.72788
9.59972	13.94543	0.65315
9.83970	12.86479	0.58580
10.07969	11.84627	0.52490
10.31967	10.88399	0.46965
10.55965	9.97278	0.41939
10.79963	9.10808	0.37355
11.03962	8.28585	0.33162
11.27960	7.50250	0.29320
11.51958	6.75481	0.25790
11.75957	6.03990	0.22540
11.99955	5.35520	0.19544
12.23953	4.69838	0.16775
12.47951	4.06732	0.14213
12.71950	3.46013	0.11838
12.95948	2.87507	0.09634
13.19946	2.31056	0.07585
13.43944	1.76516	0.05679
13.67943	1.23756	0.03903
13.91941	0.72653	0.02247
14.15939	0.23098	0.00700

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APPENDIX A

POROUS ASPHALT SURFACE COURSE CONSTRUCTION SPECIFICATIONS

Item No. 240

SUBGRADE PREPARATION FOR POROUS PAVEMENT

240.1 DESCRIPTION

The work covered by this item consists of scarifying, blading, and rolling the subgrade to obtain a uniform texture and provide, as nearly as practicable, a uniform density for the top six inches of the subgrade.

240.2 CONSTRUCTION METHODS

The subgrade shall be shaped in conformity with the typical sections shown on the plans and to the lines and grades established by the Engineer by the removal of existing material or addition of approved material. All unsuitable or otherwise objectionable material shall be removed from the subgrade and replaced with approved material. All holes, ruts and depressions shall be filled with approved material. The surface of the subgrade shall be finished to the lines and grades as established, and be in conformity with the typical sections shown on the plans. Any deviation in excess of one-half (½) inch cross-section and in a length of sixteen (16) feet measured longitudinally shall be corrected by loosening, adding, or removing material, reshaping and compacting by sprinkling and rolling, if required, to attain but not exceed the density of the natural subgrade. Sufficient subgrade shall be prepared in advance to insure satisfactory prosecution of the work. The Contractor will be required to set blue tops for the subgrade on center-line, at quarter points and curb lines at intervals not exceeding fifty (50) feet.

Material removed may be utilized in the addition of material to the subgrade if approved by the Engineer. All other material required for completion of the subgrade shall also be subject to approval by the Engineer.

The type of equipment used in subgrade preparation construction shall not cause undue subgrade compaction. Traffic over subgrade shall be kept at a minimum. Where fill is required, it shall be compacted to a density equal to the undisturbed subgrade, and inherent soft spots corrected.

240.3 MEASUREMENT

All acceptable subgrade preparation will be measured by the square yard as the area for the entire width of the roadway plus twelve (12) inches behind each curb for the entire length.

240.4 PAYMENT

This item shall be paid for at the contract unit price bid for "Subgrade Preparation for Porous Pavement", which price shall be full compensation for all work herein specified, including the furnishing of all materials, equipment, tools, labor and incidentals necessary to complete the work.

Payment will be made under:

> Pay Item No. 240: Subgrade Preparation for Porous Pavement - Per Square Yard.

Item No. 250

STONE BASE COURSE FOR STORMWATER STORAGE

250.1 DESCRIPTION

"Stone Base Course for Stormwater Storage" shall consist of a foundation course for surfacing, pavement or other base courses; shall be composed of crushed stone or gravel; and shall be constructed as herein specified in two courses in conformity with the typical sections shown on the plans and to the lines and grades established by the Engineer.

250.2 MATERIAL

The material shall be crushed as necessary to meet the requirements hereinafter specified, and shall consist of durable stone or gravel, crushed and/or screened to the required particle size. The material shall be from approved sources.

Testing of flexible base materials shall be in accordance with the following Texas Highway Department standard laboratory test procedures:

1)	Preparation for Soil Constants and Sieve Analysis	TEX-101-E
2)	Sieve Analysis	TEX-110-E
3)	Wet Ball Mill	TEX-116E

Unless otherwise specified on the plans, all base material will be stockpiled after being crushed; tested by the testing agency designated by the City of Austin; and approved by the City of Austin prior to being haul to the project site.

The material, when properly tested, shall meet the following requirements:

Course	Sieve Size	Retained on Sieve, Percent
Stone Base Course	2½"	0
	1½"	100
Stone Top Course	5/8"	0
	3/8"	100
*Max Wet Ball Mill	50	

*Unless otherwise shown on plans, the maximum increase in material passing the number 40 sieve resulting from the Wet Ball Mill Test shall not exceed 20.

250.3 CONSTRUCTION METHODS

(1) Preparation of Subgrade

The street shall be prepared and shaped in conformity with Item 240, "Subgrade Preparation for Porous Pavement", the typical sections shown on plans, and to the lines and grades as established by the Engineer. The surface of the subgrade shall be finished to line and grade, as established and in conformity with the typical section shown on plans, and any deviation in excess of ¼-inch in cross-section and in a length of 10 feet measured longitudinally shall be corrected by loosening, adding or removing material and reshaping. Sufficient subgrade shall be prepared in advance to insure satisfactory prosecution of the work. Material excavated in the preparation of the subgrade shall be utilized in the construction of slopes or otherwise disposed of as directed. Any additional material required for the completion of slopes shall be secured from sources indicated on plans or designated by the Engineer. Blue tops shall be set by the Contractor for subgrade on center-line, quarter points and curb lines at intervals not exceeding fifty (50) feet.

(2) Stone Base Course

Immediately before placing the stone base material, the subgrade shall be checked as to conformity with grade and section.

The material shall be delivered in approved vehicles of a uniform capacity and it shall be the charge of the Contractor that the required amount of specified material be delivered in each 100-foot station.

Stone base course shall be laid over a dry subgrade to the depth shown in drawings, in lifts to lay naturally compacted. The stone base course is not to be rolled or compacted and is to be kept clean from debris, clay, and eroding soil.

(3) Stone Top Course

This course is to be two inches in depth. Construction methods shall be the same as prescribed for the stone base course. Blue tops shall be set by the Contractor for finished base grade on center-line and intermediate points not exceeding 11 feet between points at 50-foot intervals.

250.4 MEASUREMENT

"Stone Base Course", including "Stone Top Course", will be measured by the square yard at depths specified in the proposal for the area of Parking Lot, as shown on the typical sections of the plans or otherwise provided for in the contract documents, complete in place; by the cubic yard, loose vehicle measurement; or by the cubic yard, complete in place, as indicated in the proposal.

250.5 PAYMENT

This item will be paid for at the contract unit price bid for "Stone Base Course", which price shall be full compensation for all work herein specified, including the furnishing, hauling, and placing of all materials, for all water required and for all equipment, tools, labor and incidentals necessary to complete the work.

Payment will be made under:

Pay Item No. 250-A: Stone Base Course (complete in place) - Per Square Yard, or

Pay Item No. 250-B: Stone Base Course (loose vehicle measurement) - Per Cubic Yard, or

Pay Item No. 250-C: Stone Base Course (complete in place) - Per Cubic Yard.

Item No. 380

HOT MIX POROUS ASPHALT PAVEMENT

380.1 DESCRIPTION

This item shall consist of a surface course as shown on the plans, composed of a lightly compacted mixture of mineral aggregate and asphaltic material.

The pavement shall be constructed on the previously completed and approved subgrade and stone base course as herein specified and in accordance with the details shown on the plans.

380.2 MATERIALS

(1) Coarse Aggregate

The mineral aggregate shall be composed of a coarse aggregate, a fine aggregate, and if required, a mineral filler. Samples of coarse aggregate and mineral filler shall be submitted for testing, as directed by the Engineer, and approval of both material and of the source of supply must be obtained from the Engineer prior to delivery.

(a) Coarse Aggregate

Coarse aggregate shall be that part of the aggregate retained on the No. 8 sieve; shall consist of clean, tough, durable fragments of crushed stone, or crushed gravel, as hereinafter specified, of uniform quality throughout.

When the coarse aggregate is tested in accordance with Test Method Tex-217-F (Part I, Separation of Deleterious Material), the amount of organic matter, clay, loam or particles coated therewith or other undesirable materials shall not exceed two percent and when remaining part of the sample is further tested in accordance with Test Method Tex-127-F (Part II, Decantation), the amount of material removed shall not be more than two percent.

The coarse aggregate shall have an abrasion of not more than forty percent loss by weight when subjected to the Los Angeles Abrasion Test, Test Method Tex-410-A.

Unless specified otherwise, gravel shall be so crushed that seventy-five percent of the particles retained on the No. 4 sieve shall have more than one crushed face when tested in accordance with Test Method Tex-413-A (Particle Count).

(b) Fine Aggregate

The fine aggregates shall be that part of the aggregate passing the No. 8 sieve and shall consist of sand, screenings, or combination thereof as hereinafter specified, of uniform quality throughout.

Fine aggregate shall consist of durable particles, free from injurious foreign matter. Screenings shall be of the same or similar material as specified for coarse aggregate. The plasticity index of that part of the fine aggregate passing the No. 40 sieve shall be not more than 6 when tested in accordance with Test Method Tex-106-E. Fine aggregate from each source shall meet plasticity requirements.

Where stone screenings are specified for use, the stone screenings shall meet the following grading requirements unless otherwise shown on plans:

	Percent by Weight
Passing the ½" Sieve	100
Passing the No. 200 Sieve	10-30

When authorized by the Engineer, stone screenings containing particles larger than ½" may be used but only that portion of the material passing the 3/8" sieve shall be considered as fulfilling the requirements for screenings when a minimum percentage of screenings is specified for a particular mixture.

(c) Mineral Filler

Mineral filler shall consist of thoroughly dry stone dust, slate dust, portland cement, fly ash or other mineral dust approved by the Engineer. The mineral filler shall be free from foreign and other injurious matter.

When tested by Test Method Tex-200-F (Dry Sieve Analysis), it shall meet the following grading requirements:

	Percent by Weight
Passing a No. 30 Sieve	95-100
Passing a No. 80 Sieve, not less than	75
Passing a No. 200 Sieve, not less than	55

(2) Asphaltic Material for Porous Asphalt Paving Mixture

Asphalt for the paving mixture shall be asphalt cement, viscosity grade AC-20, and shall meet the requirements of the Item, "Asphalts, Oil and Emulsions". The Contractor shall notify the Engineer of the source of his asphaltic material prior to production of the asphaltic mixture and this source shall not be changed during the course of the project except on written permission of the Engineer.

The paving mixture shall consist of a uniform mixture of coarse aggregate, fine aggregate, asphaltic material and mineral filler, if required.

The grading of each constituent of the mineral aggregate shall be such as to produce, when properly proportioned, a mixture which, when tested in accordance with Test Method Tex-200-F (Dry Sieve Analysis), will conform to the limitations for master grading given below:

	Percent by Weight
Passing ½" Sieve	100
Passing 3/8" Sieve, Retained on No. 4 Sieve	40-65
Passing No. 4 Sieve, Retained on No. 8 Sieve	3-35
Passing No. 8 Sieve, Retained on No. 16 Sieve	1-20
Passing No. 16 Sieve, Retained on No. 200 Sieve	0-10
Passing No. 200 Sieve	2-5

The asphaltic material shall form from 5.5 to 6.0 percent of the mixture by weight unless specified otherwise on the plans.

The Engineer will designate the exact grading of the aggregate and asphalt content, within the above limits, to be used in the mixture. The paving mixture produced should not vary from the designated grading and asphalt content by more than the tolerances allowed herein; however, the mixture produced shall conform to the limitations for master grading specified above.

	Percent by Weight
Passing ½" Sieve, Retained on 3/8" Sieve	±5
Passing 3/8" Sieve, Retained on No. 4 Sieve	±5
Passing No. 4 Sieve, Retained on No. 8 Sieve	±5
Total Retained on No. 8 Sieve	±5
Passing No. 8 Sieve, Retained on No. 16 Sieve	±3
Passing No. 16 Sieve, Retained on No. 200 Sieve	±3
Passing No. 200 Sieve	±3
Asphalt Material	±0.25

Should the paving mixture produced vary from the designated grading and asphalt content by more than the above tolerances, proper changes are to be made until it is within these tolerances.

Samples of the mixture, when tested in accordance with Test Method Tex-210-F, shall not vary from the grading proportions of the aggregate and the asphalt content designated by the Engineer by more than the respective tolerances specified above, and shall be within the limits specified for master grading.

380.4 EQUIPMENT

(1) Mixing Plants

Mixing plants that will not continuously meet all the requirements of this specification shall be condemned.

Mixing plants may be either the weight-batching type or the continuous mixing type. Both types of plants shall be equipped with satisfactory conveyors, power units, aggregate handling equipment, aggregate screens and bins, and shall consist of the following essential pieces of equipment:

(a) Weight-Batching Type

Cold Aggregate Bin and Proportioning Device. The cold aggregate bins or aggregate stockpiles shall be of sufficient number and size to supply the amount of aggregate required to keep the plant in continuous operations. The proportioning device shall be such as will provide a uniform and continuous flow of aggregate in the desired proportion to the plant.

Dryer. The dryer shall be of the type that continually agitates the aggregate during heating and in which the temperature will be so controlled that aggregate will not be injured in the necessary drying and heating operations required to obtain a mixture of the specified temperature.

The burner, or combination of burners, and type of fuel used shall be such that in the process of heating the aggregate to the desired or specified temperatures, no residue from the fuel shall adhere to the heated aggregate.

A recording thermometer shall be provided which will record the temperature of the aggregate when it leaves the dryer. The dryer shall be of sufficient size to keep the plant in continuous operation.

Screenings and Proportioning. The screening capacity and size of the bins shall be sufficient to screen and store the amount of aggregate required to properly operate the plant and keep the plant in continuous operation at full capacity. Proper proportions shall be made to enable inspection forces to have easy and safe access to the proper location on the mixing plant where accurate representative samples of aggregate may be taken from the bins for testing. Separation of hot bin into compartments will not be required providing uniform grading and asphalt content are consistently produced in the completed mix.

Aggregate Weigh Box and Batching Scales. The aggregate weigh box and batching scales shall be of sufficient capacity to hold and weigh a complete batch of aggregates. The weigh box and scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment".

Asphaltic Material Bucket and Scales. The asphaltic material bucket and scales shall be of sufficient capacity to hold and weigh the necessary asphaltic material for one batch. If the material is measured by weight, the bucket and scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment".

If a pressure-type flow meter is used to measure the asphaltic material, the requirements of the Item, "Weighing and Measuring Equipment", shall apply.

Mixer. The mixer shall be of the pug mill type and shall have a capacity of not less than 20 cubic feet unless otherwise shown on the plans. The number of blades and the position of same shall be such as to give a uniform and complete circulation of the batch in the mixer. The mixer shall be equipped with an approved spray bar that will distribute the asphaltic material quickly and uniformly throughout the mixer. Any mixer that has a tendency to segregate the mineral aggregate or fails to secure a thorough and uniform mixing with the asphaltic material shall not be used. This shall be determined by mixing the standard batch for the required time, then dumping the mixture and taking samples from its different parts. This will be tested by the extraction test and must show that the batch is uniform throughout. All mixers shall be provided with an automatic time lock that will lock the discharge doors of the mixer for the required mixing period. The dump door or doors and the shaft seals of the mixer shall be tight enough to prevent spilling of aggregate or mixture from the pug mill.

(b) Continuous Mixing Type

Cold Aggregate Bin and Proportioning Device. Same as for weight-batching type of plant.

Dryer. Same as for weight-batching type of plant.

Screening and Proportioning. Same as for weight-batching type of plant.

Aggregate Proportioning Device. The hot aggregate proportioning device shall be so designed that when properly operated a uniform and continuous flow of aggregate into the mixer will be maintained.

Asphaltic Material Spray Bar. The asphaltic material spray bar shall be designed such that the asphalt will spray uniformly and continuously into the mixer.

Asphaltic Material Meter. An accurate asphaltic material recording meter shall be placed in the asphalt line leading to the spray bar so that the cumulative amount of asphalt used can be accurately determined. Provisions of a permanent nature shall be made for checking the accuracy of the meter output. The asphalt meter and line to the meter shall be protected with a jacket of hot oil or other approved means to maintain the temperature of the line and meter near the temperature specified for the asphaltic material.

If a pressure-type flow meter is used to measure the asphaltic material, the requirements of the Item, "Weighing and Measuring Equipment", shall apply.

Mixer. The mixer shall be of the pug mill continuous type and shall have a capacity of not less than 40 tons of mixture per hour. Any mixer that has a tendency to segregate the aggregate or fails to secure a thorough and uniform mixing of the aggregate with the asphaltic material shall not be used. The dam gate at the discharge end of the pug mixer and/or pitch of the mixing paddles shall be so adjusted as to maintain a level of mixture in the pug mixer between the paddle shaft and the paddle tips (except at the discharge end).

Truck Scales. A set of standard platform truck scales, conforming to the Item, "Weighing and Measuring Equipment", shall be placed at a location approved by the Engineer.

(2) Asphaltic Material Heating Equipment

Asphaltic material heating equipment shall be adequate to heat the amount of asphaltic material required to the desired temperature. Asphaltic material may be heated by steam coils which shall be absolutely tight. Direct fire heating of asphaltic material will be permitted, provided the heater used is manufactured by a reputable concern and there is positive circulation of the asphalt throughout the heater. Agitation with steam or air will not be permitted. The heating apparatus shall be equipped with a recording thermometer with a 24-hour chart that will record the temperature of the asphaltic material at the highest temperature.

(3) Spreading and Finishing Machine

The spreading and finishing machine shall be of a type approved by the Engineer, shall be capable of producing a surface that will meet the requirements of the typical cross-section and a surface test when required and, when the mixture is dumped directly into the finishing machine, shall have adequate power to propel the delivery vehicles in a satisfactory manner. The finishing machine shall be equipped with a flexible spring and/or hydraulic type hitch sufficient in design and capacity to maintain contact between the rear wheels of the hauling equipment and the pusher rollers of the finishing machine while the mixture is being unloaded.

The use of any vehicle which requires dumping directly into the finishing machine and which the finishing machine cannot push or propel in such a manner as to obtain the desired lines and grades without resorting to hand finishing will not be allowed.

Automatic screed controls, if required, shall meet the requirements of the Item, "Automatic Screed Controls for Asphaltic Concrete Spreading and Finishing Machines".

(4) Pneumatic Tire Rollers

The rollers shall be acceptable light pneumatic tire rollers conforming to the requirements of the Item, "Rolling (Pneumatic Tire)", unless otherwise specified on plans.

The tire pressure of each tire shall be adjusted as directed by the Engineer and this pressure shall not vary by more than 5 pounds per square inch.

(5) Two-Axle Tandem Roller

This roller shall be an acceptable power-driven tandem roller weighing not less than 6 tons, nor more than 10 tons.

(6) Three Wheel Roller

This roller shall be an acceptable power-driven three-wheel roller weighing not more than 10 tons.

(7) All Equipment shall be maintained in good repair and operating condition and shall be approved by the Engineer.

(8) Alternate Equipment

When permitted by the Engineer in writing, equipment other than that specified which will consistently produce satisfactory results may be used.

380.5 STOCKPILING, STORAGE, PROPORTIONING AND MIXING

(1) Aggregate Storage

If the mineral aggregates are stored or stockpiled, they shall be handled in such a manner as to prevent segregation, mixing of the various materials or sizes, and contamination with foreign materials. The grading of aggregates proposed for use and as supplied to the mixing plant shall be uniform. Suitable equipment of acceptable size shall be furnished by the Contractor to work the stockpiles and prevent segregation of the aggregates.

(2) Storage and Heating of Asphaltic Materials

The asphaltic material storage shall be ample to meet the requirements of the plant. Asphalt shall not be heated to a temperature in excess of that specified in the Item, "Asphalts, Oils and Emulsions". All equipment used in the storage and handling of asphaltic material shall be kept in a clean condition at all times and shall be operated in such a manner that there will be no contamination with foreign matter.

(3) Feeding and Drying of Aggregate

The feeding of various sizes of aggregate to the dryer shall be done through the cold aggregate bin and proportioning device in such a manner that a uniform and constant flow of materials in the required proportions will be maintained. When specified on the plans, the cold aggregate bins shall be charged by use of a clamshell, dragline, shovel or front-end loader. The aggregate shall be dried and heated to the temperature necessary to produce a mixture having the specified temperature.

(4) Proportioning

The proportioning of the various materials entering the asphaltic mixture shall be as directed by the Engineer and in accordance with these specifications. Aggregate shall be proportioned by weight using the weigh box and batching scales herein specified when the weight-batch type of plant is used and by volume using the hot aggregate proportioning device when the continuous mixer type of plant is used. The asphaltic material shall be proportioned by weight or by volume based on weight using the specified equipment.

(5) Mixing

(a) Batch-Type Mixer

In the charging of the weigh box and in the charging of the mixer from the weigh box, such methods or devices shall be used as are necessary to secure a uniform asphaltic mixture. In introducing the batch into the mixer, the mineral aggregate shall be introduced first; shall be mixed thoroughly for a period of 5 to 20 seconds, as directed, to uniformly distribute the various sizes throughout the batch before the asphaltic material is added; the asphaltic material shall then be added and the mixing continued for a total mixing period of not less than 30 seconds. This mixing period may be increased if, in the opinion of the Engineer, the mixture is not uniform.

(b) Continuous-Type Mixer

The amount of aggregate and asphaltic material entering the mixer and the rate of travel through the mixer shall be so coordinated that a uniform mixture of the specified grading and asphalt content will be produced. Checks on asphalt used shall be made at least twice daily by comparing the asphalt used in ten loads of completed mix as shown on the asphalt recording meter and the design amount for these ten loads. The acceptable percent of variation between the asphalt used and the design amount will be as shown on the plans or as determined by the Engineer.

(c) The Mixture

The mixture produced from each type of mixer shall not vary from the specified mixture by more than the tolerances herein specified.

(d) The Surface Mixture

The surface mixture from each type of mixer will not exceed a temperature of 260°F, and shall be specified by the

Engineer. The temperature of the mixture will not be lower than 180°F when placed on the road.

380.6 CONSTRUCTION METHODS

(1) The surfacing mixture shall not be placed when the air temperature is below 50°F and is falling, but it may be placed when the air temperature is above 40°F and is rising. The air temperature shall be taken in the shade away from artificial heat. It is further provided that the surfacing mixture shall be placed only when the humidity, general weather conditions and temperature and moisture condition of the pavement surface, in the opinion of the Engineer, are suitable.

(2) Transporting the Surface Mixture

The mixture, prepared as specified above, shall be hauled to the work in tight vehicles with smooth dump beds that have been previously cleaned of all foreign material. The dispatching of vehicles shall be arranged so that all material delivered may be placed, and all rolling shall be completed during daylight hours. In cool weather or for long hauls, canvas covers and insulating of the truck bodies may be required. The inside of the truck body shall be sprayed with a non-petroleum release agent satisfactory to the Engineer, if necessary, to prevent the mixture from adhering to the body.

(3) Placing

The asphaltic mixture shall be dumped directly into the specified spreading and finishing machine and spread on the approved prepared surface in such a manner that, when properly compacted, the finished surface will be smooth and of uniform texture and density. The spreading and finishing machine shall be operated at a speed satisfactory to the Engineer. During application of asphaltic material, care shall be taken to prevent splattering of adjacent pavement, curb and gutter and structures.

(4) Compacting

(a) As directed by the Engineer, the surface mixture shall be compressed lightly and uniformly with the specified rollers and/or other approved rollers.

(b) Compaction of the surface course shall be done while the surface is cool enough to resist the roller used. One or two passes by the roller is all that is required, as excess rolling could cause a reduction in surface course porosity.

(c) The motion of the rollers shall be slow enough at all times to avoid displacement of the mixture. If any displacement occurs, it shall be corrected at once by the use of rakes and of fresh mixture where required. To prevent adhesion of the surfacing mixture to the roller, the wheels shall be kept thoroughly moistened with a soap-water solution. Necessary precautions shall be taken to prevent the dropping of gasoline, oil, grease or other foreign matter on the pavement, either when the rollers are in operation or when standing.

(5) Surface Tests

The surface of the pavement, after compaction, shall be smooth and true to the established line, grade and cross-section, and when tested with a 10-foot straightedge, the maximum deviation shall not exceed ¼-inch in 10 feet, and any point in the surface not meeting this requirement shall be corrected as directed by the Engineer. The completed surface shall meet the approval of the Engineer for riding surface finish and appearances.

(6) After final rolling, no vehicular traffic of any kind shall be permitted on the porous pavement until cooling or hardening has taken place, as directed by the Engineer, but in no case less than six hours.

380.7 MEASUREMENT

(1) The surfacing mixture will be measured separately by the ton of 2,000 pounds of "Asphalt" and by the cubic yard of dry, loose "aggregate" of the type actually used in the completed and accepted work in accordance with the plans and specifications for the project. The volume of aggregate in the compacted mix shall be calculated from the measured weights of the surfacing mixture by use of the following formula:

$$V = \frac{(W - A)}{(27)K}$$

where V = Cubic yards of aggregate, dry, loose
W = Total weight of surfacing mixture, in pounds
A = Weight of Asphalt, in pounds
K = Unit Weight of Aggregate, in pounds per cubic foot.

The value "K" shall be the average of two or more tests determined by the Engineer in the following manner:

At the beginning of plant operations, a specified weight of dried mineral aggregate shall be placed in an acceptable container that will contain a minimum volume of three cubic yards. The aggregate shall be leveled or "struck-off" and measured, to determine the volume of the mineral aggregate, in cubic feet. The unit weight of the mineral aggregate shall be obtained by dividing the specified weight of dried aggregate in pounds by the measured volume in cubic feet. The value "K" is an average of two or more of the above-described tests.

The value "K" shall be checked a minimum of one time for each 3,000 cubic yards or mineral aggregate. If, in the opinion of the Engineer or the Contractor's representative, the value of "K" has changed, a check test shall be made. A new value for "K" shall be determined if the checked value of "K" varies more than two percent (plus or minus) from the value being used.

The weight "W", if mixing is done by a continuous mixer, will be determined by truck scales. The weight, if batched, will be determined on batch scales, and records of the number of batches, batch designs and weight of "Asphalt" and "Aggregate" shall be kept.

380.8 PAYMENT

(1) The work performed and materials furnished as prescribed by this item and measured as provided under "Measurement", will be paid for at the unit prices bid for "Asphalt" and "Aggregate", of the types specified, which prices shall each be full compensation for quarrying, furnishing all materials and freight involved; for all heating, mixing, hauling, cleaning the existing pavement, placing asphalt-aggregate surfacing mixture, rolling and finishing; and for all manipulations, labor, tools, equipment and incidentals necessary to complete the work.

(2) All templates, straightedges, scales and other weighing and measuring devices necessary for the proper construction, measuring and checking of the work shall be furnished, operated and maintained by the Contractor at his expense.

APPENDIX B

COMPUTER PROGRAM LISTINGS

PROGRAM PORPAV (REVISED C7/01/82 BY GFG)

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C     PROGRAM PORPAV  (REVISED 07/01/82 BY GFG)
C
      DIMENSION TITLE(20),SURF(150),DRAIN(150),QFLO(150)
      DIMENSION C(5),S(5),L(5),W(5),RAIN(25)
      DIMENSION INFLOW(150),TOTFLO(150)
      REAL KGI,KGF
      REAL L,KP,KS,KG,KD,KO,KI,INFLOW,INFLOP,KPT,KGT,KST,KDT
      DATA INFLOW/150*0.0/
      READ(5,11)TITLE
      WRITE(6,50)TITLE
      READ(5,*) IAREA, NRAIN, KSTEP, JRUNOF
      WRITE(6,52) IAREA, NRAIN, KSTEP, JRUNOF
      IF(IAREA.EQ.0)GO TO 13
      READ(5,*) (C(I), S(I), L(I), W(I), I=1,IAREA)
      WRITE(6,54)
      WRITE(6,56) (I, C(I), S(I), L(I); W(I), I=1,IAREA)
 13   IF (JRUNOF.EQ.0) GO TO 14
      READ(5,*) (INFLOW(J), J=1,JRUNOF)
      GO TO 16
   14 READ(5,*) (RAIN(N), N=1,NRAIN)
      WRITE(6,58)
      WRITE(6,60)(RAIN(N), N=1,NRAIN)
   16 READ(5,*) TSTHR, TSTMIN, TI
      WRITE(6,61)TI
      READ(5,*) KP,DP,PORP, KS,DS,PORS; KGI,KGF,DECAY, XXQ
      DECAY=DECAY/60.
      READ(5,*) WID,XLEN,SPAVE,XN,ISEAL
      READ(5,*) SURDEP,STORP,STORS,DEDDEP,DB
C
      DO 17 J=1,JPUNOF
 17   INFLOW(J)=INFLOW(J)*TI*720./XLEN/WID
C
C
C
      STMXP=PORP*DP/100.0
      STMXS=PORS*DS/100.0
      WRITE(6,80) KP,DP,PORP,STORP,STMXP
      WRITE(6,82) KS,DS,PORS,STORS,STMXS
      WRITE(6,84)KGI,KGF,DECAY,STORG
      WRITE(6,85)XXQ
      WRITE(6,86) WID,XLEN,SPAVE,XN,DEDDEP,SURDEP
C
      DO 136 K=1,NRAIN
      INFLOW(K)=INFLOW(K)+RAIN(K)/60.*TI
  136 CONTINUE
  200 WRITE(6,70)
      WRITE(6,60) (INFLOW(K),K=1,KSTEP)
      KPT=KP*TI/60.0
      KST=KS*TI/60.0
      ITP=(DP*60./KP/TI)+1
      ITS=(DS*60./KP/TI)+1
      XXT=XXQ*TI/60.0
      KDT=KD*TI/60.0
      CONV=XLEN*WID/60./12./TI
C
      WRITE(6,78)TITLE
C
```

```
      DO 900 K=1,KSTEP
C
      T=TI*(K-1.)
      OEVAP=0.0
      INFLOP=INFLOW(K)+SURDEP
C
C     COMPUTATION OF INITIAL SURFACE STORAGE
C
      IF (INFLOP.LE.KPT) GO TO 300
      KPOUNT=KPOUNT+1
      STORP=STORP+KPT
      IF(STORP.GE.STMXP)KITP=1
      OVERTP=KITP*KPT
      STORP=STORP-OVERTP
      IF(STORP.LE.0.)STORP=0.0
      SURDEP=INFLOP-KPT
      GO TO 304
C
  300 STORP=STORP+INFLOP
      KPOUNT=KPOUNT+1
      IF(STORP.GE.STMXP)KITP=1
      IF(KPOUNT.GE.(STMXP/KPT))KITP=1
      OVERTP=KITP*KPT
      STORP=STORP-OVERTP
      IF(STORP.LE.0.)OVERTP=OVERTP+STORP
      IF(STORP.LE.0.)STORP=0.0
      SURDEP=0.0
C
C     COMPUTATION OF FLOW THROUGH POROUS PAVEMENT
C
  304 STORS=STORS+OVERTP
      KG=KGF+(KGI-KGF)*2.71828**(-1.0*DECAY*T)
      KGT=KG*TI/60.0
      IF(STORS.LT.KGT)GO TO 305
      OVERTS=KGT
      GO TO 306
  305 OVERTS=STORS
  306 STORS=STORS-OVERTS
C
      IF(ISEAL.EQ.0.0)GO TO 307
      IF(STORS/PORS*100.LT.(DB/PORS*100.))GO TO 307
      C1=KS*SPAVE/2./12./XLEN
      C2=KS/2./12./12./XLEN/XLEN
      D=STORS/PORS*100.-DB/PORS*100
      OHORS=C1*D+C2*D*D*TI/60.
      IF(OHORS.GE.(STORS-DB))OHORS=(STORS-DB)
      IF(OHORS.GE.XXT)OHORS=XXT
      STORS=STORS-OHORS
      IF(STORS.LE.0.)STORS=0.0
      GO TO 308
  307 OHORS=0.0
  308 CONTINUE
C
C
C
C
C
```

```
 460  STORG=STORG+OVERTS
  520 IF (STORS.LE.STMXS) GO TO 525
      STORP=STORP+STORS-STMXS
      OVERTP=OVERTP+STORS-STMXS
      STORS=STMXS
  525 IF (STORP.LE.STMXP) GO TO 530
      SURDEP=SURDEP+STORP-STMXP
      STORP=STMXP
      IF(SURDEP.LE.DEDDEP) GO TO 620
  530 IF(SPAVE.LE.0.0)SPAVE=(SURDEP-DEDDEP)/XLEN/12.
C
C     COMPUTATION OF OUTFLOWS AND VELOCITY
C
      DIFDEP=SURDEP-DEDDEP
      IF(DIFDEP.LE.0.)GO TO 620
      VEL=1.486*(DIFDEP/12.0)**0.667*SPAVE**0.5/XN
  600 OSURF=VEL*DIFDEP/12.*WID
  605 OSURF=12.0*OSURF*TI*60./(WID*XLEN)
      IF(OSURF.GT.DIFDEP)OSURF=DIFDEP
      GO TO 615
  620 OSURF=0.0
  615 SURDEP=SURDEP-OSURF
      SURF(K)=OSURF*CONV
      DRAIN(K)=OHORS*CONV
      QFLO(K)=SURF(K)+DRAIN(K)
      TOTFLO(K)=QFLO(K)/CONV
      WRITE(6,72)       T,INFLOW(K),OEVAP,INFLOP,OSURF,OVERTP,OHORP,
     1OVERTS,OHORS,OVERTG,SURDEP,STORP,STORS,STORG
  900 CONTINUE
      WRITE(6,90)TITLE
      WRITE(6,60)(SURF(K),K=1,KSTEP)
      WRITE(6,92)
      WRITE(6,60)(DRAIN(K),K=1,KSTEP)
      WRITE(6,94)
      WRITE(6,60)(QFLO(K),K=1,KSTEP)
C
      DO 920 K=1,KSTEP
      TOTIN=TOTIN+INFLOW(K)
      IF(K.EQ.1)GO TO 921
      IF(INFLOW(K-1).NE.0.0.AND.INFLOW(K).LE.0.00005)TINT=K-1
  921 TOTVOL=TOTVOL+TOTFLO(K)
      IF(QFLO(K).GT.QPEAK)TPEAK=(K-1)*TI
      IF(QFLO(K).GT.QPEAK)QPEAK=QFLO(K)
      IF((TOTFLO(K)*CONV).GE.0.00005)TDUR=TDUR+1.0
      IF(TDUR.EQ.1.0)TSTART=K-1.0
      TINUM=TINUM+INFLOW(K)*K
  920 TNUM=TNUM+TOTFLO(K)*(K-TSTART)
C
      IF(TINT.EQ.0.0)TINT=FLOAT(K)
      TIN=TOTIN/TINT*60.0/TI
      TDUR=(TDUR+2.0-TSTART)*TI
      IF(TOTVOL.EQ.0.0)GO TO 922
      TMASS=TNUM/TOTVOL
      TIMASS=TINUM/TOTIN
      TDFT=(TSTART+TMASS-TIMASS)*TI
      TSTART=(TSTART-1)*TI
      GO TO 924
  922 TMASS=999.
      TDET=999.
      TSTART=999.
      TDUR=999.
      TPEAK=999.
      QPEAK=0.0
C
  924 WRITE(6,925)TIN,TOTIN,TOTVOL,QPEAK,TSTART,TPEAK,TDUR,TDET
      WRITE(7,925)TIN,TOTIN,TOTVOL,QPEAK,TSTART,TPEAK,TDUR,TDET
  925 FORMAT(/////,11X,'AVERAGE',5X,'STORM',4X,'RUNOFF',6X,'PEAK',
     .4X,'RUNOFF',3X,'TIME TO',4X,'RUNOFF',7X,'LAG',/,9X,
     .'INTENSITY',4X,'VOLUME',4X,'VOLUME',6X,'FLOW',5X,'BEGAN',
     .6X,'PEAK',2X,'DURATION',6X,'TIME',//,8X,8F10.4)
C
      DO 901 K=1,KSTEP
      T=TI*(K-1)
  901 WRITE(7,902)T,QFLO(K)
  902 FORMAT(2F10.5)
      WRITE(7,903)
  903 FORMAT('999,999')
C
 2000 CONTINUE
C
C
   11 FORMAT(20A4)
   50 FORMAT(1H1,25X,///,5X,21HPOROUS PAVEMENT MODEL,///2(10X,20A4/)///)
   52 FORMAT(10X,33HNUMBER OF CONTRIBUTORY SUBAREAS =, 7X,I5,/,
     1        10X,35HNUMBER OF RAINFALL TIME INTERVALS =, 5X,I5,/,
     2        10X,31HNUMBER OF COMPUTATIONAL STEPS =, 9X,I5,/,
     3        10X,33HNUMBER OF RUNOFF TIME INTERVALS =, 7X,I5,/////)
   54 FORMAT(15X,23HSUBAREA CHARACTERISTICS,//,
     4        10X,7HSUBAREA,8X,9HROUGHNESS,6X,5HSLOPE,9X,6HLENGTH,9X,5HWI
     5DTH,    10X,7H NUMBER,8X,9H  COEFF   ,/)
   56 FORMAT(13X,I2,12X,F5.3,8X,F5.3,10X,F6.1,9X,F6.1)
   58 FORMAT(10X,///,25X,26HINPUT RAINFALL DATA, IN/HR,//)
   60 FORMAT(5X,10F10.3)
   61 FORMAT(///,10X,27HCOMPUTATIONAL TIME INTERVAL,F10.3,2X,7HMINUTES)
   62 FORMAT(/////,25X,22HINPUT EVAPORATION DATA,//,10X,13HSTARTING TIME
     6,F5.0,2HHR,F5.0,3HMIN,//,10X,21HEVAPORATION DEPTH FOR,I5, 8H DAYS
     7IS,F9.3,7H INCHES,//,10X,56HEVAPORATIVE INCREASE DUE TO SURFACE HE
     8AT ABSORBTION IS =,F6.1,' PERCENT',/)
   64 FORMAT(////////////!//,25X,55HIZZARD'S DIMENSIONLESS HYDROGRAPH CONS
     1TANTS FOR SUBAREA,I5,
     1  //,5X,3HKO=,F6.3,4X,3HKI=,F6.3,4X,3HVE=,F6.3,4X,3HQE=,F6.3,4X,3H
     2TE=,F6.3,4X,3HVO=,F6.3,/)
   66 FORMAT(////,25X,49HCOMPUTED HYDROGRAPH FOR RAINFALL INCREMENT NUMB
     3ER,I5,9H   IN CFS,//)
   68 FORMAT(1H1,/////,25X,63HCUMULATIVE INFLOW HYDROGRAPH FOR ALL RAINF
     4ALL INCREMENTS IN CFS,//)
   69 FORMAT(////,25X,66HCUMULATIVE INFLOW HYDROGRAPH FOR ALL RAINFALL I
     1NCREMENTS IN INCHES,//)
   70 FORMAT(1H1,/////,25X,47HTOTAL INFLOW ONTO THE POROUS PAVEMENT IN I
     5NCHES,//)
   71 FORMAT(19X,16H***** AT TIME T=,2X,F4.0,2X,41HVELOCITY IS TOO HIGH
     1FOR LAMINAR FLOW, V=,F6.3,2X,3HFPS,2X,5H*****)
   72 FORMAT(5X,F4.0,9F8.4,4F9.4)
   78 FORMAT(1H1,/////,45X,32HPOROUS PAVEMENT MODELING RESULTS,//1(
     425X,20A4/)//,40X,41HIN UNITS OF INCHES EXCEPT TIME IN MINUTES,///,
     55X,4HTIME,2X,6HINFLOW,3X,5HOEVAP,2X,6HINFLOP,3X,5HOSURF,
     62X,6HOVERTP,3X,5HOHOPP,2X,6HOVERTS,3X,5HOHORS,2X,6HOVERTG,
     M3X,6HSURDEP,4X,5HSTORP,4X,5HSTORS,4X,5HSTORG,//)
   80 FORMAT(1H1,/////,25X,31HPOROUS PAVEMENT CHARACTERISTICS,///,
     135X,5HPERM.,5X,5HDEPTH,4X,6HPOROS-,5X,5HINIT.,6X,4HMAX.,/,
     235X,5HCOEFF,5X,         9X,6H ITY   ,5X,5HSTOR.,5X,5HSTOR.,/,
     335X,5HIN/HR,6X,3HIN.,5X,7HPERCENT,5X,3HIN.,7X,3HIN.,//,
     410X,8HPAVEMENT,12X,5F10.3,/)
   82 FORMAT(10X,8HSUBGRADE,12X,5F10.3,/)
   84 FORMAT(10X,14HNATURAL GROUND,6X,7F10.3,/)
   85 FORMAT(10X,16HARTIFICIAL DRAIN,4X,F10.3)
   86 FORMAT(/////,15X,19HWIDTH OF PAVEMENT =,26X,F10.3,4H  FT,/,
     1                 15X,20HLENGTH OF PAVEMENT =,25X,F10.3,4H  FT,/,
     2                 15X,19HSLOPE OF PAVEMENT =,26X,F10.3,7H  FT/FT,/,
     3                 15X,34HMANNING COEFFICIENT FOR PAVEMENT =,11X,F10.3,
     4               /,
     5                 15X,26HDEAD STORAGE ON PAVEMENT =,19X,F10.3,4H  IN,/,
     6                 15X,29HINITIAL STORAGE ON PAVEMENT =,16X,F10.3,4H  IN
     7)
   10 FORMAT(10X,4I5)
   15 FORMAT(10X,4F10.3)
   20 FORMAT(10X,7F10.3)
   25 FORMAT(10X,3F10.3)
   30 FORMAT(10X,I10,F10.3,F10.3)
   35 FORMAT(10X,11F5.3)
   40 FORMAT(10X,5F10.3,1F5.2,1I5)
   41 FORMAT(10X,6F10.3)
   90 FORMAT(1H1,///1(25X,20A4/)///,32X,33HSURFACE RUNOFF HYDROGRAPH, IN
     1 CFS,//)
   92 FORMAT(/////,29X,'HYDROGRAPH OF OUTFLOW THROUGH BASE, IN CFS',//)
 94   FORMAT(/////,29X,'TOTAL OUTFLOW HYDROGRAPH, IN CFS',//)
      CALL EXIT
      END
```

PROGRAM PAVDES

```
C      PROGRAM PAVDES
C
       REAL IS,IR,NB,N,L,I,KP,KB,KF
C
C      DEFINE FUNCTIONS
C
       F(T,DB)=(DI-C1*DB-C2*DB**2)/NB
       G(T,DS)=C3-C4*DS**(5./3.)
       H(T,DB)=(IS+C1*DB+C2*DB**2)/NB
C
C      READ IN DATA
C
       READ(5,*)IR,QC,TR,AC,V
       READ(5,*)KP,KB,L,AP,S,SB,NB,IS,N,KF,QP
       WRITE(1,2)IR,QC,TR,AC,V,KP,KB,L,AP,S,SB,NB,IS,N,KF,QP
       WRITE(6,2)IR,QC,TR,AC,V,KP,KB,L,AP,S,SB,NB,IS,N,KF,QP
  2    FORMAT(5X,'STORM AND PAVEMENT CHARACTERISTICS',//,
      .5X,'AVERAGE RAINFALL INTENSITY (IN/HR)',F10.3,/,
      .5X,'AVERAGE RUNOFF RATE (CFS)          ',F10.3,/,
      .5X,'RAINFALL DURATION (HOURS)          ',F10.3,/,
      .5X,'CONTRIBUTING AREA (SQ. FT.)        ',F10.3,/,
      .5X,'VOLUME TO DETAIN (INCHES)          ',F10.3,/,
      .5X,'PAVEMENT PERMEABILITY (IN/HR)      ',F10.3,/,
      .5X,'BASE PERMEABILITY (IN/HR)          ',F10.3,/,
      .5X,'PAVEMENT LENGTH (FT)               ',F10.3,/,
      .5X,'PAVEMENT AREA (SQ FT)              ',F10.3,/,
      .5X,'SURFACE SLOPE (FT/FT)              ',F10.3,/,
      .5X,'BASE LAYER SLOPE (FT/FT)           ',F10.3,/,
      .5X,'BASE POROSITY (CU FT/CU FT)        ',F10.3,/,
      .5X,'SOIL INFILTRATION RATE (IN/HR)     ',F10.3,/,
      .5X,'MANNINGS N (FT1/6/SEC)             ',F10.3,/,
      .5X,'FILTER CLOTH PERMEABILITY (IN/HR) ',F10.3,/,
      .5X,'MAXIMUM ALLOWABLE DISCHARGE (CFS) ',F10.3)
C
C      EXECUTE METHODOLOGY
C
       C1=KB*SB/24/L
       C2=KB/288/L/L
       I=43200*QC/AP+IR
       DI=I-IS
       TS=TR
       IF(V.LT.(TR*IR-.1))TS=V*(AC+AP)/AP/I
C
       DT=TS/250.
       T=0.
       DB=0.

       WRITE(6,3)
  3    FORMAT(//////////,15X,'             TIME ','   DEPTH IN BASE',
      .'     DISCHARGE  ',//)
       WRITE(6,1)T,DB,QB
  1    FORMAT(15X,3F15.5)
C
C      FILLING THE BASE LAYER
C
       DO 10 NSTEP=1,250
       DEL1=DT*F(T,DB)
      DEL2=DT*F(T+.5*DT,DB+.5*DEL1)
      DEL3=DT*F(T+.5*DT,DB+.5*DEL2)
      DEL4=DT*F(T+DT,DB+DEL3)
      DB=DB+0.166667*(DEL1+2.*DEL2+2.*DEL3+DEL4)
      QB=C1*DB+C2*DB**2
      T=T+DT
      IF((NSTEP/10*10).NE.NSTEP)GO TO 10
      WRITE(6,1)T,DB,QB
   10 CONTINUE
C
      TF=T
      BASE=DB
      BASEQ=QB
      DELT=TR-TS
      IF(DELT.LE.0)GO TO 25
C
C     SUPFACE RUNOFF CALCULATIONS
C
      DS=0.0001
      C3=DI-QB
      C4=1021*S**0.5/N/L
      WRITE(6,1)T,DS,QS
C
      NUP=DELT/DT
      DO 20 NSTEP=1,NUP
      DEL1=DT*G(T,DS)
      DEL2=DT*G(T+.5*DT,DS+.5*DEL1)
      DEL3=DT*G(T+.5*DT,DS+.5*DEL2)
      DEL4=DT*G(T+DT,DS+DEL3)
      DS=DS+0.166667*(DEL1+2.*DEL2+2.*DEL3+DEL4)
      QS=C4*DS**(5./3.)
      T=T+DT
      IF((NSTEP/10*10).EQ.NSTEP)WRITE(6,1)T,DS,QS
 20   CONTINUE
C
C     DRAINING THE BASE LAYER
C
   25 DO 30 NSTEP=1,1000
      DEL1=DT*H(T,DB)
      DEL2=DT*H(T+.5*DT,DB+.5*DEL1)
      DEL3=DT*H(T+.5*DT,DB+.5*DEL2)
      DEL4=DT*H(T+DT,DB+DEL3)
      DB=DB-0.166667*(DEL1+2.*DEL2+2.*DEL3+DEL4)
      QB=C1*DB+C2*DB**2
      T=T+DT
      IF(DB.LE.0.0)GO TO 100
      IF((NSTEP/10*10).NE.NSTEP)GO TO 30
      WRITE(6,1)T,DB,QB
   30 CONTINUE
C
  100 TD=T-TF-DELT
      V=(I*TF-IS*(TF+TD))*AP/12
      BASEQ=BASEQ*AP/43200
      QS=QS*AP/43200
      WRITE(1,40)BASE,TF,BASEQ,TD,V,DS,QS
      WRITE(6,40)BASE,TF,BASEQ,TD,V,DS,QS
 40   FORMAT(///////,5X,'DEPTH OF THE BASE LAYER IS',F5.1,'  INCHES.',/,
     .5X,'THE TIME TO FILL THE BASE LAYER IS',F6.2,'  HOURS.',/,
     .5X,'THE MAXIMUM BASE DISCHARGE IS',F8.3,'  CFS.',/,
     .5X,'THE TIME TO DRAIN THE BASE LAYER IS',F6.2,'  HOURS.',/,
     .5X,'THE TOTAL VOLUME DISCHARGED FROM THE BASE IS',F10.0,
     .2X,'CUBIC FEET',/,5X,'THE MAXIMUM SURFACE DEPTH IS',F6.2,
     .'  INCHES.',/,5X,'THE MAXIMUM SURFACE DISCHARGE IS',F7.3,'  CFS.')
C
      STOP
      END
```

APPENDIX C

RESULTS OF FIELD AND LABORATORY ANALYSES FOR THE CITY OF AUSTIN STUDY

```
                 POROUS ASPHALT LOT AT THE KRAMER LN MAINTENANCE YARD
              STORM DATE =   MAR,22,82
              STORM NO. =         1  NUMBER OF SAMPLES =        6
SA    Q     TKN        NO3        TN         COD        TSS          ZN        PB        TIME
NO   CFS   MG/L       MG/L       MG/L       MG/L       MG/L         MG/L      MG/L        MIN
          10**-2     10**-2     10**-2     10**-2     10**-2       10**-2    10**-2
 1  0.000    0.0        0.0        0.0        0.0        0.0          0.0       0.0        0.0

 2  0.008  628.0      780.0     1408.0    11900.0   337500.0          8.4       1.7        6.0

 3  0.194  157.0      112.0      269.0     6670.0   104500.0          3.8       2.6       20.0

 4  0.269  147.0      102.0      249.0     2920.0    51600.0          2.0       1.8       33.0

 5  0.269   74.0       70.0      144.0     2710.0    32700.0          2.4       1.6       40.0

 6  0.194   42.0       78.0      120.0     2300.0    11700.0          1.3       2.9       60.0

              TOTAL FLOW AND POLLUTANTS.
              **********************************

  VO       STKN     SNO3        STN       SCOD       STSS           SZN        SPB
CU.FT       LB       LB          LB         LB         LB            LB         LB
10**1   10**-5   10**-5      10**-5     10**-5     10**-5        10**-5    10**-5
0.00       0.0      0.0         0.0        0.0         0.0        0.000      0.000

0.14      56.5     70.2       126.7     1071.0     30375.0        0.756      0.153

8.63     889.0    664.1      1553.1    36438.7    584486.1       20.905     13.939

26.68   2548.0   1815.2      4363.2    69392.7   1166824.3       43.477     34.254

37.98   3070.5   2309.5      5380.0    88528.7   1394196.3       60.424     45.905

65.76   3799.8   3663.8      7463.5   128462.4   1597337.3       82.995     96.777

              RUNOFF AND POLLUTANT PER UNIT AREA.
              *****************************************

  VO       TKN      NO3        TN          COD         TSS         ZN         PB
  IN     LB/AC    LB/AC      LB/AC       LB/AC       LB/AC       LB/AC      LB/AC
        10**-5   10**-5     10**-5      10**-5      10**-5      10**-5     10**-5
 0.51  10733.8  10349.0    21083.4    362888.1   4512252.0    234.449    273.381

              AVERAGE POLLUTANTS IN THE SAMPLE.
              **********************************

 TKN        NO3        TN         COD          TSS        ZN        PB
MG/L       MG/L       MG/L       MG/L         MG/L       MG/L      MG/L
10**-2     10**-2     10**-2     10**-2       10**-2     10**-2    10**-2
  92.6       89.2      181.8     3129.1      38907.9       2.0       2.4
```

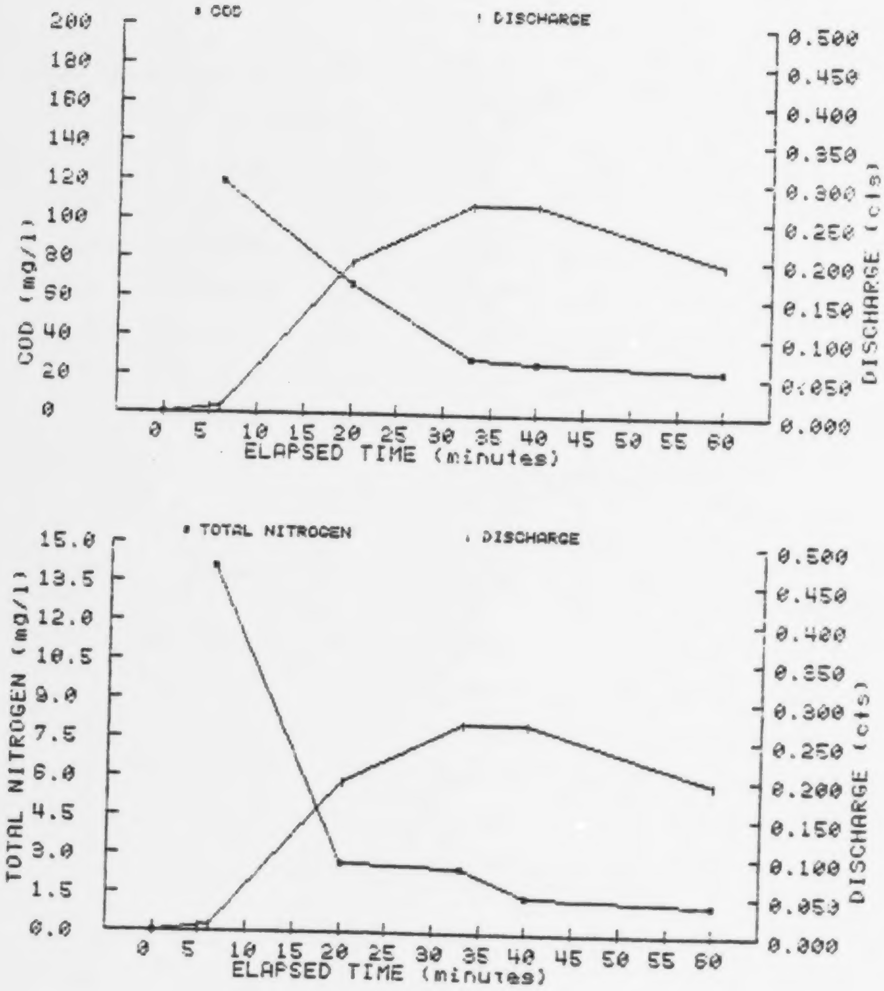


FIG. C-1 . COD AND TOTAL NITROGEN VALUES RECORDED 3/22/82.

POROUS ASPHALT LOT

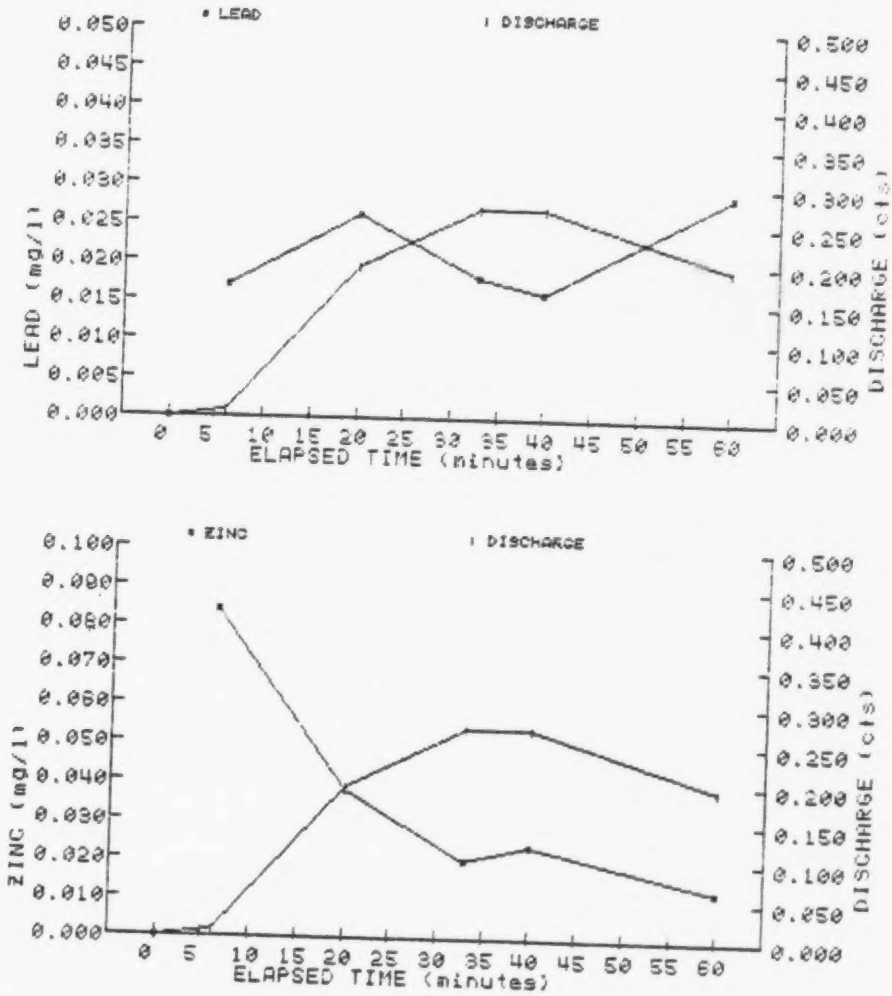


FIG.C-2 . LEAD AND ZINC VALUES RECORDED 3/22/82.

POROUS ASPHALT LOT

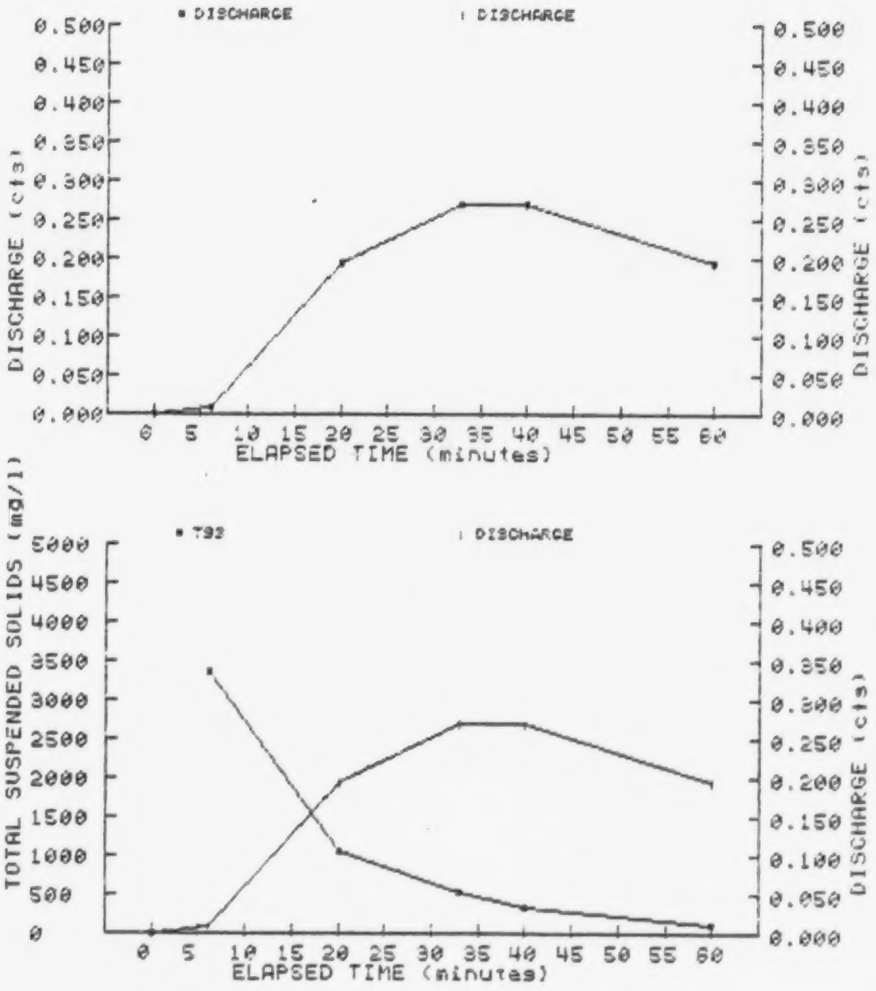


FIG. C-3 . DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/22/82

POROUS ASPHALT LOT

```
             POROUS ASPHALT LOT AT THE KRAMER LN MAINTENANCE YARD
          STORM DATE =    APR,05,82
          STORM NO. =          2  NUMBER OF SAMPLES =          6
SA    Q      TKN        NO3        TN         COD        TSS         ZN         PB         TIME
NO   CFS    MG/L       MG/L       MG/L       MG/L       MG/L       MG/L       MG/L        MIN
           10**-2     10**-2     10**-2     10**-2     10**-2     10**-2     10**-2
 1  0.000      0.0        0.0        0.0        0.0        0.0        0.0        0.0        0.0
 2  0.001    575.0      290.0      865.0    18700.0    26900.0        4.1        0.7        2.0
 3  0.181    278.0      120.0      398.0     6010.0    33300.0        3.8        1.4       12.0
 4  0.253    162.0       85.0      247.0     3400.0    20500.0        2.7        0.7       30.0
 5  0.194    133.0       67.0      200.0      240.0    13400.0        2.0        0.7       46.0
 6  0.034    118.0       67.0      185.0      240.0     4210.0        0.5        0.6       90.0
          TOTAL FLOW AND POLLUTANTS.
          ********************************

  VO       STKN      SNO3       STN        SCOD        STSS         SZN        SPB
 CU.FT       LB        LB        LB          LB          LB          LB         LB
 10**1   10**-5    10**-5    10**-5      10**-5      10**-5      10**-5     10**-5
 0.00       0.0       0.0       0.0         0.0         0.0       0.000      0.000
 0.01       2.2       1.1       3.2        70.1       100.9       0.015      0.003
 5.47     950.8     410.6    1361.4     20579.2    113737.1      12.983      4.780
28.90    3323.7    1655.6    4979.3     70380.7    414010.8      52.531     15.619
50.36    5107.3    2554.1    7661.3     73599.1    593704.6      79.351     25.006
80.45    7326.8    3814.4   11141.2     78113.5    672894.6      88.756     35.916
          RUNOFF AND POLLUTANT PER UNIT AREA.
          ****************************************

  VO      TKN       NO3        TN          COD         TSS          ZN         PB
  IN     LB/AC     LB/AC      LB/AC       LB/AC       LB/AC       LB/AC      LB/AC
        10**-5    10**-5     10**-5      10**-5      10**-5      10**-5     10**-5
 0.63  20933.8   10898.0    31832.0    223181.4   1922556.3     253.589    102.618
          AVERAGE POLLUTANTS IN THE SAMPLE.
          *********************************

 TKN       NO3        TN         COD          TSS         ZN          PB
 MG/L      MG/L       MG/L       MG/L         MG/L        MG/L        MG/L
10**-2    10**-2     10**-2     10**-2       10**-2      10**-2      10**-2
 145.9      75.9      221.8     1555.3      13397.5         1.8         0.7
```

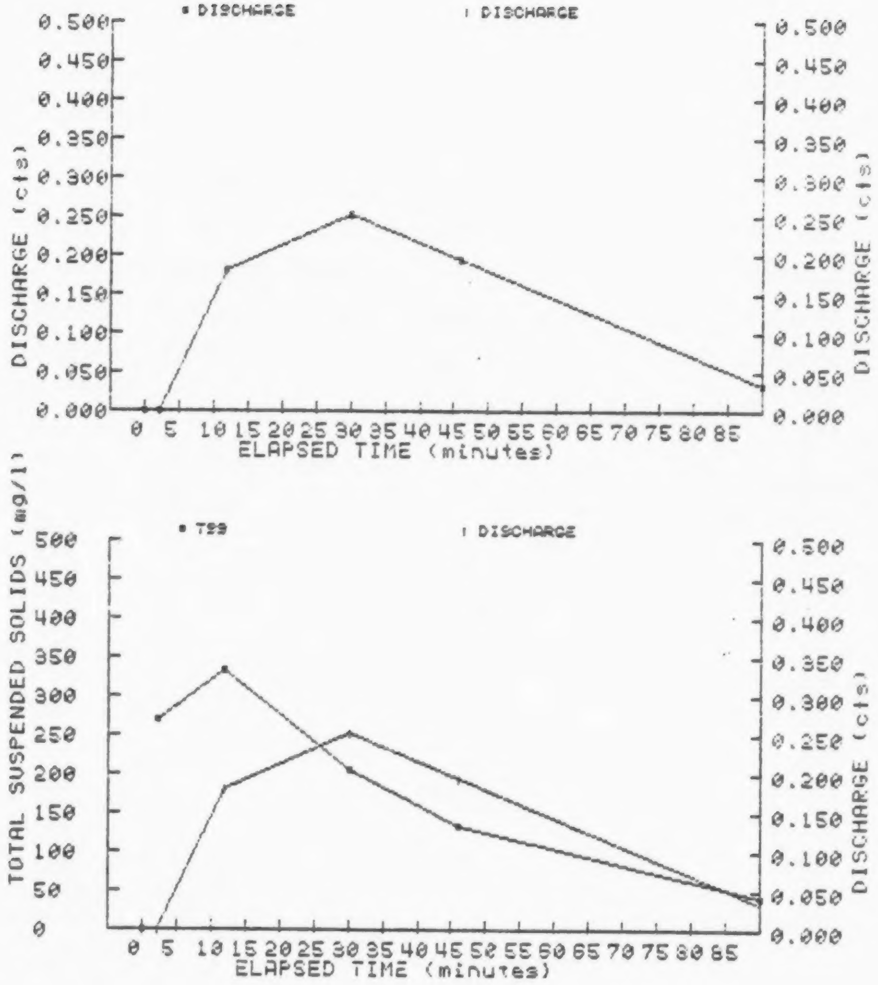


FIG. C-4 . DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 4/5/82.

POROUS ASPHALT LOT

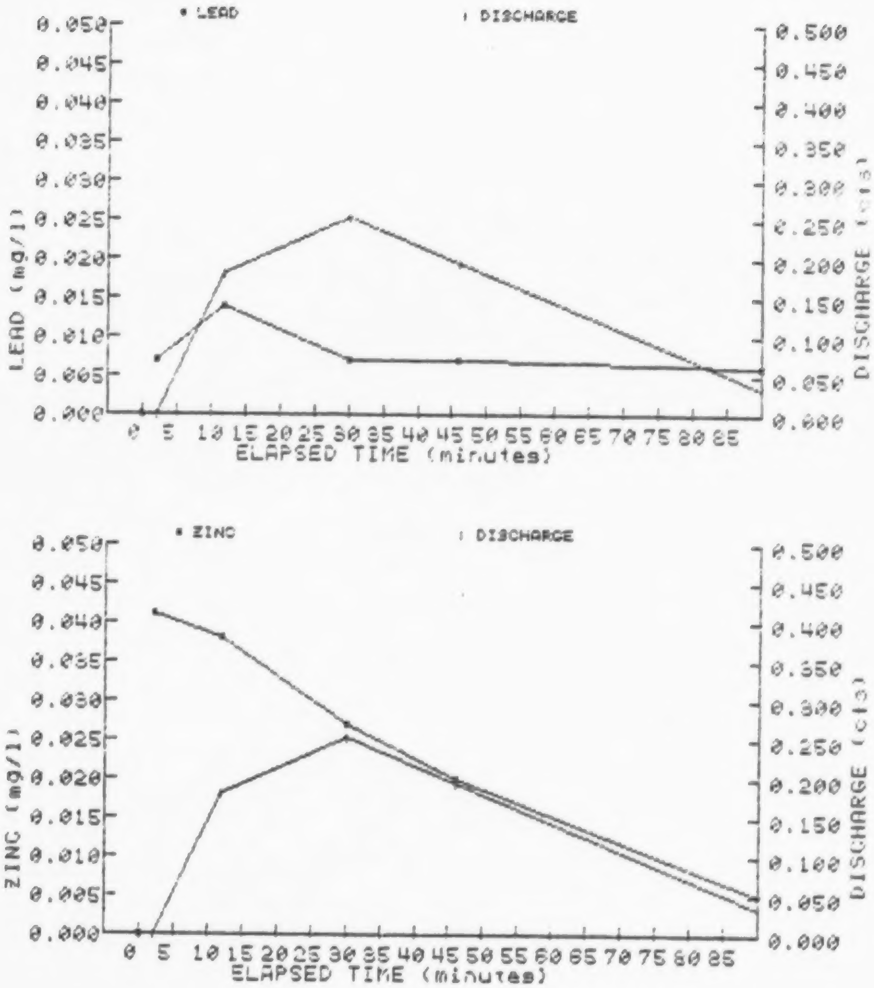


FIG.C-5 . LEAD AND ZINC VALUES RECORDED 4/5/82.

POROUS ASPHALT LOT

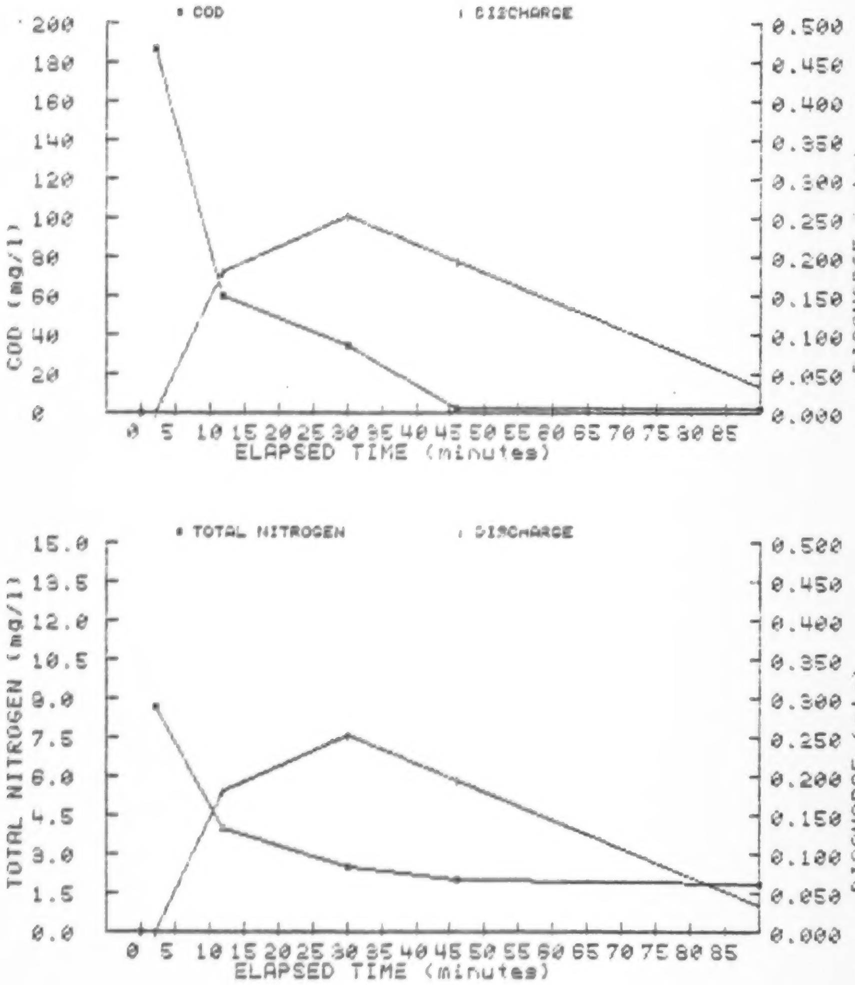


FIG. C-6 . COD AND TOTAL NITROGEN VALUES RECORDED 4/5/82.

POROUS ASPHALT LOT

```
               POROUS ASPHALT LOT AT THE CITY OF AUSTIN KRAMER LN MAINTENANCE YARD
             STORM DATE =    JUN,01,82
             STORM NO. =          3  NUMBER OF SAMPLES =          6
 SA     Q        TKN                    TN
 NO    CFS      MG/L       NO3         MG/L       COD        TSS         ZN
              10**-2      MG/L       10**-2      MG/L       MG/L        MG/L       PB        TIME
                         10**-2                 10**-2     10**-2      10**-2     MG/L       MIN
  1  0.000       0.0         0.0         0.0        0.0         0.0                10**-2
                                                                          0.0        0.0       0.0
  2  0.000   389.0       168.0       557.0      6040.0     44600.0       8.8        0.9       1.0
  3  0.169   289.0       185.0       474.0      5040.0     19400.0       5.7        1.0      10.0
  4  0.237   370.0       115.0       485.0      4830.0      3500.0       7.4        2.4      20.0
  5  0.123   360.0       123.0       483.0      1380.0      5500.0       5.6        0.8      55.0
  6  0.008   344.0        97.0       441.0      3970.0       210.0       4.1        1.4     115.0
           TOTAL FLOW AND POLLUTANTS.
           *********************************

  VO         STKN       SNO3          STN         SCOD         STSS           SZN          SPB
 CU.FT         LB         LB           LB           LB           LB            LB           LB
 10**1     10**-5     10**-5       10**-5       10**-5       10**-5        10**-5       10**-5
 0.00         0.0        0.0          0.0          0.0          0.0         0.000        0.000

 0.00         0.0        0.0          0.0          0.0          0.0         0.000        0.000

 4.56       824.2      527.6       1351.8      14373.4      55326.4        16.256        2.766

 16.74     3640.8     1403.0       5043.9      51141.8      81970.1        72.588       20.884

 54.54    12145.8     4308.9      16454.7      83744.3     211907.6       204.888       40.493

 78.12    17215.5     5738.4      22954.0     142252.2     215002.4       265.312       61.273
          RUNOFF AND POLLUTANT PER UNIT AREA.
          ****************************************

  VO       TKN        NO3          TN           COD          TSS          ZN          PB
  IN      LB/AC      LB/AC        LB/AC        LB/AC        LB/AC        LB/AC       LB/AC
          10**-5     10**-5      10**-5        10**-5       10**-5       10**-5      10**-5
 0.61   48631.4    16210.0      64841.7      401842.3     607351.4     749.468     173.087
          AVERAGE POLLUTANTS IN THE SAMPLE.
          *********************************

 TKN        NO3          TN          COD          TSS          ZN          PB
 MG/L       MG/L        MG/L        MG/L         MG/L         MG/L        MG/L
10**-2     10**-2      10**-2      10**-2       10**-2       10**-2      10**-2
 353.0      117.7       470.7      2916.8       4408.5          5.4         1.3
```

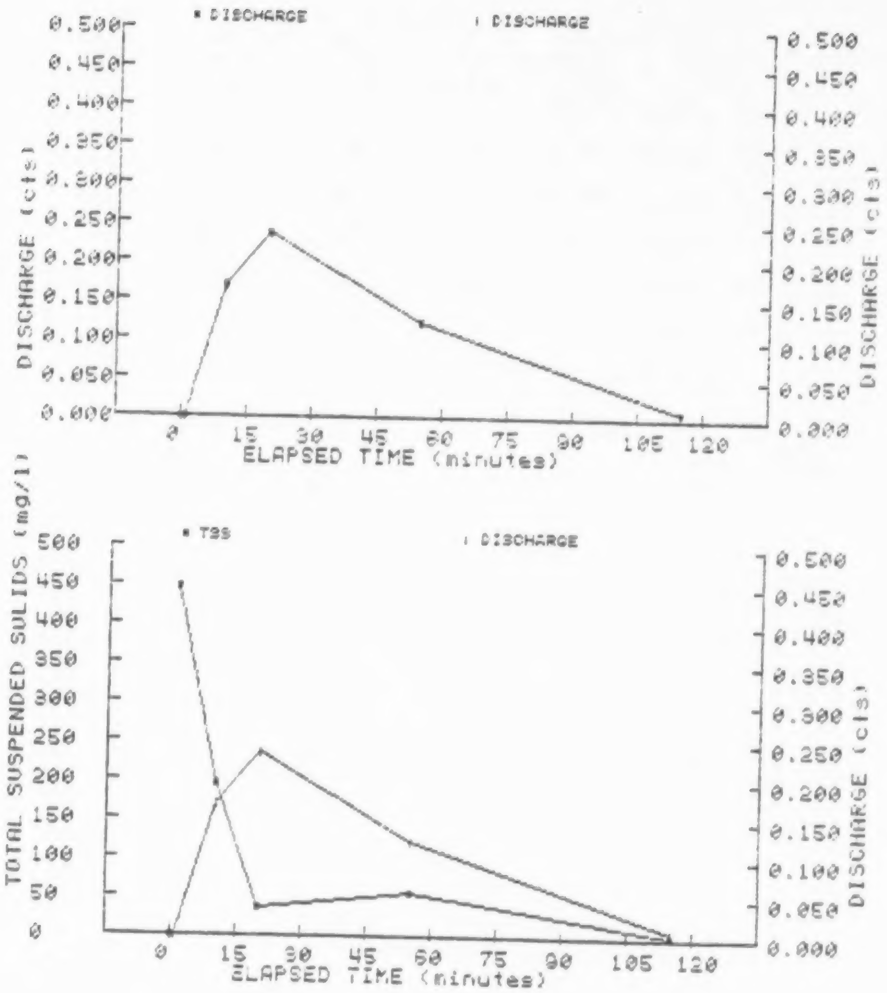


FIG.C-7 . DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 6/1/82.

POROUS ASPHALT LOT

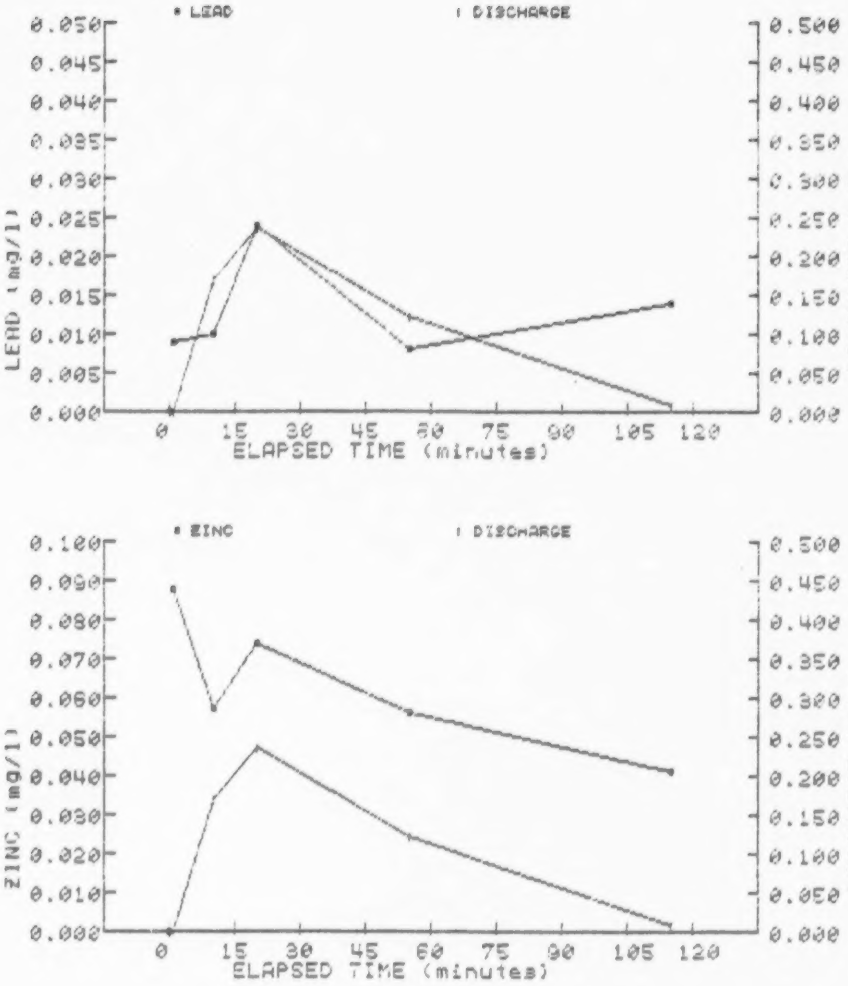


FIG. C-8 . LEAD AND ZINC VALUES RECORDED 6/1/82.

POROUS ASPHALT LOT

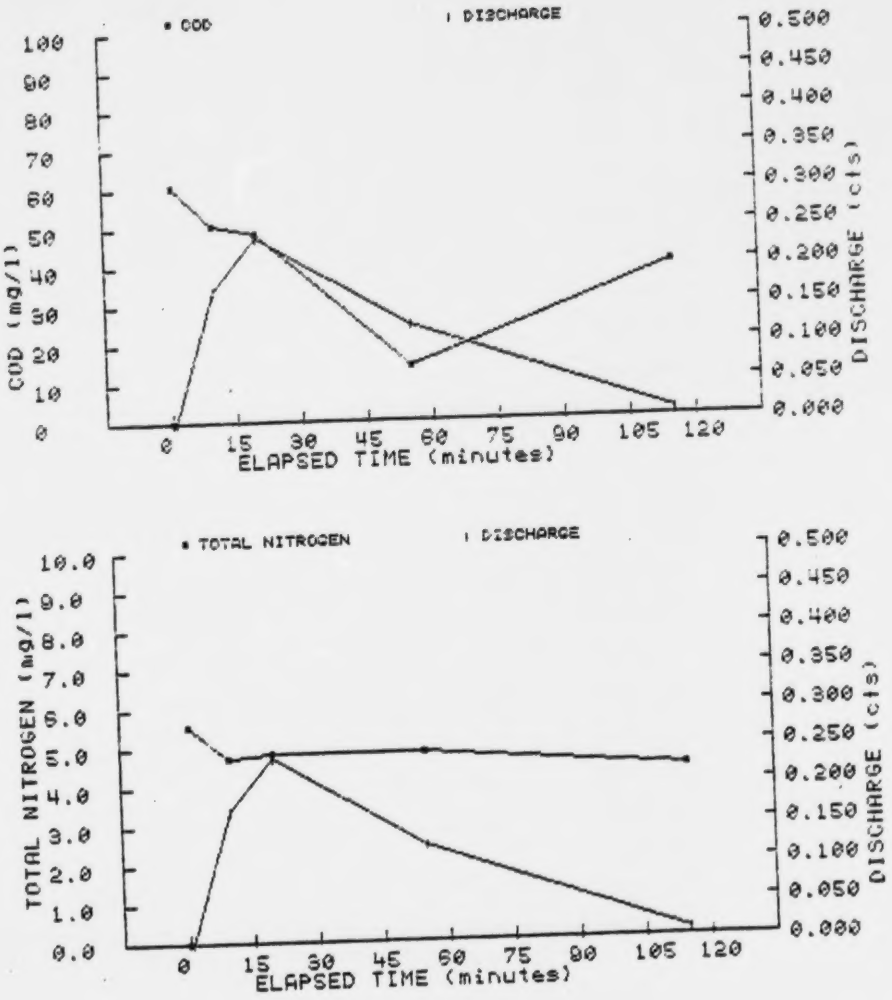


FIG. C-9 . COD AND TOTAL NITROGEN VALUES RECORDED 6/1/82.

POROUS ASPHALT LOT

TSS

```
EQUATION                     A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))         2.95741    1.16073     0.21655       4.84735
Y = A(EXP(BX))            0.08148    0.00733     0.29542      10.46580          15
Y = A(X**B)               0.04881    0.77204     0.92265       4.84069          15
Y = A + BX                2.09132    0.00872     0.22992       4.80583          15
                                                                                15
```

COD

```
EQUATION                     A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))         0.34634    0.14581     0.46985       0.34006          15
Y = A(EXP(BX))            0.01603    0.00799     0.37993       1.39172          15
Y = A(X**B)               0.01244    0.67934     0.98092       0.17663          15
Y = A + BX                0.14500    0.00140     0.81362       0.20195          15
```

TN

```
EQUATION                     A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))         0.03469    0.01628     0.27558       0.05794          15
Y = A(EXP(BX))            0.00154    0.00723     0.49196       0.13414          15
Y = A(X**B)               0.00175    0.58444     0.90440       0.04862          15
Y = A + BX                0.00047    0.00019     0.74064       0.03467          15
```

Pb

```
EQUATION                     A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))         0.00156    0.00071     0.30311       0.00235          15
Y = A(EXP(BX))            0.00007    0.00710     0.49131       0.00626          15
Y = A(X**B)               0.00011    0.48418     0.64377       0.00241          15
Y = A + BX                0.00033    0.00001     0.66126       0.00164          15
```

Zn

```
EQUATION                     A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))         0.00389    0.00180     0.24954       0.00684          15
Y = A(EXP(BX))            0.00020    0.00689     0.49616       0.01352          15
Y = A(X**B)               0.00027    0.50431     0.74874       0.00661          15
Y = A + BX                0.00035    0.00002     0.62330       0.00485          15
```

```
              LATTICE BLOCK LOT LOCATED AT SYMPHONY SQUARE AUSTIN
          STORM DATE =    MAR,02,82
          STORM NO. =         1  NUMBER OF SAMPLES =          6
SA    Q     TKN        NO3        TN        COD        TSS          ZN         PB        TIME
NO   CFS   MG/L       MG/L       MG/L      MG/L       MG/L         MG/L       MG/L        MIN
          10**-2     10**-2     10**-2    10**-2     10**-2       10**-2     10**-2
 1  0.000     0.0        0.0        0.0        0.0        0.0          0.0        0.0        0.0

 2  0.018  126.0       32.0      158.0     4720.0     8030.0          2.4        0.0        7.0

 3  0.030  115.0       29.0      144.0     2270.0     3240.0          9.2        0.2       25.0

 4  0.034  144.0       24.0      168.0     2500.0     4780.0          0.5        0.0       45.0

 5  0.034   98.0       20.0      118.0     2210.0     3820.0          1.6        0.4       55.0

 6  0.001  126.0       20.0      146.0     2590.0      660.0          1.3        2.2      105.0
          TOTAL FLOW AND POLLUTANTS.
          **********************************

 VO        STKN      SNO3         STN        SCOD        STSS           SZN         SPB
CU.FT        LB        LB          LB          LB          LB            LB          LB
10**1    10**-5    10**-5      10**-5      10**-5      10**-5        10**-5      10**-5
0.00        0.0       0.0         0.0         0.0         0.0         0.000       0.000

0.38       29.8       7.6        37.3      1115.1      1897.1         0.567       0.012

2.97      216.1      54.5       270.6      4792.5      7145.9        15.471       0.287

6.81      561.7     112.1       673.8     10792.5     18617.9        16.671       0.407

8.85      686.6     137.6       824.3     13610.2     23488.4        18.711       0.943

14.10    1100.1     203.3      1303.3     22108.7     25654.0        22.977       8.227
          RUNOFF AND POLLUTANT PER UNIT AREA.
          ****************************************

 VO      TKN       NO3          TN          COD         TSS          ZN          PB
 IN     LB/AC     LB/AC       LB/AC       LB/AC        LB/AC        LB/AC       LB/AC
        10**-5    10**-5      10**-5       10**-5      10**-5       10**-5       10**-5
0.27    7692.7    1421.0      9114.1     154606.1    179398.6     160.676      57.532
          AVERAGE POLLUTANTS IN THE SAMPLE.
          *********************************

TKN       NO3         TN         COD          TSS          ZN          PB
MG/L      MG/L       MG/L       MG/L         MG/L         MG/L        MG/L
10**-2    10**-2     10**-2     10**-2       10**-2       10**-2      10**-2
125.0       23.1      148.1     2511.7       2914.5          2.6         0.9
```

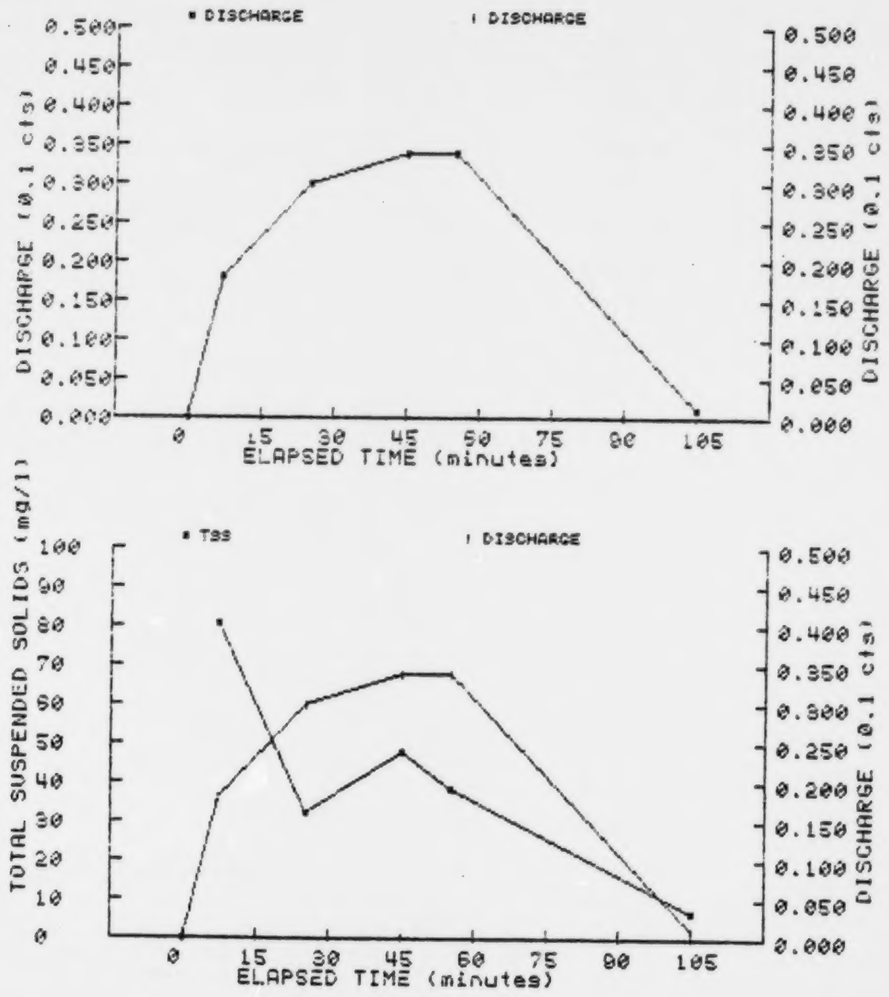


FIG. C-10. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/2/82.

LATTICE BLOCK LOT

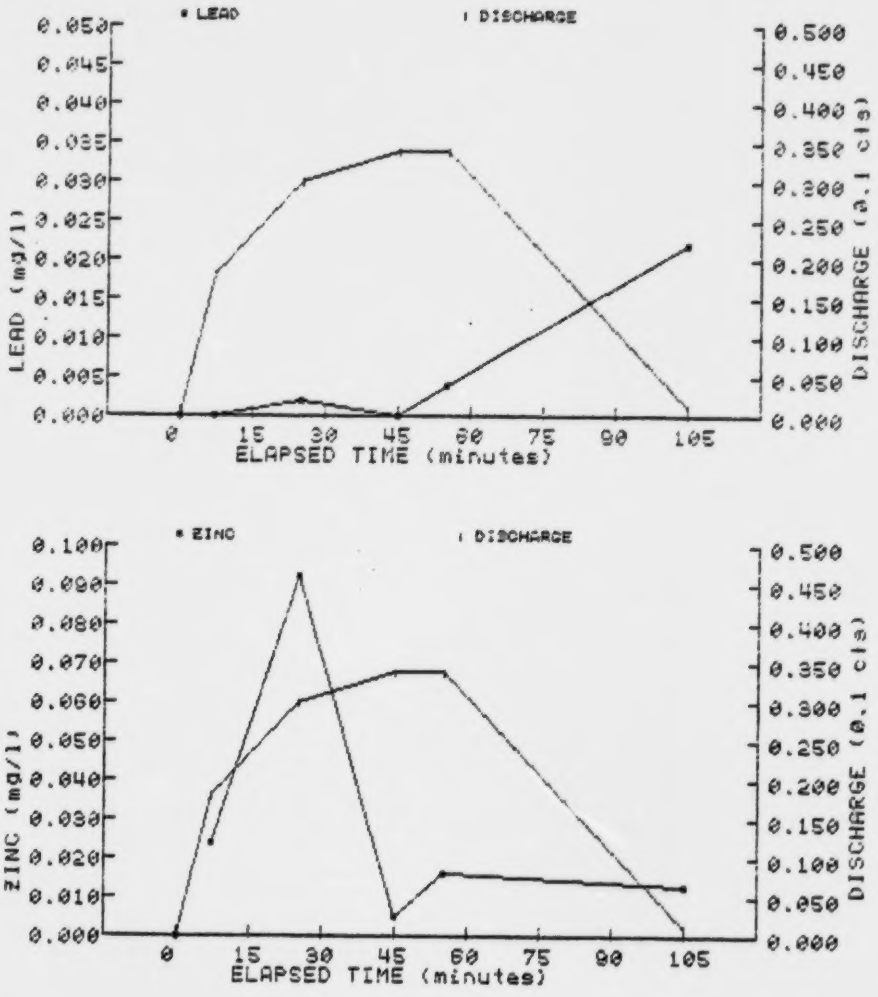


FIG. C-11. LEAD AND ZINC VALUES RECORDED 3/2/82.

LATTICE BLOCK LOT

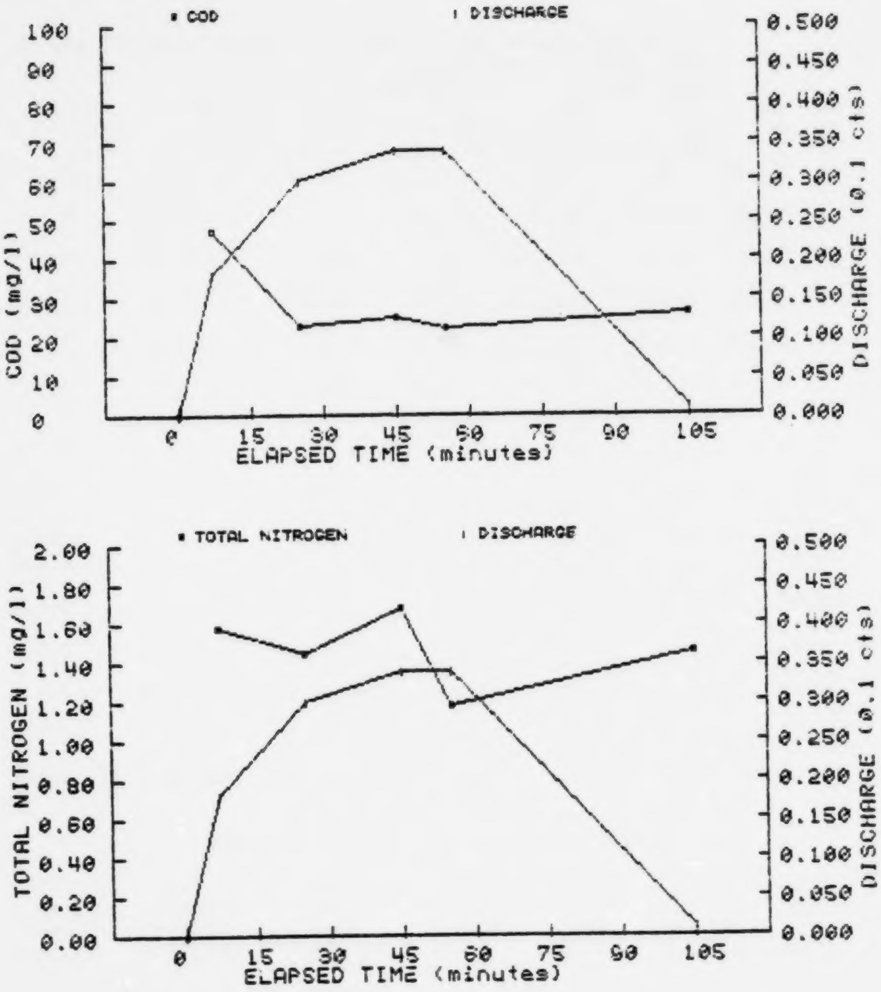


FIG.C-12. COD AND TOTAL NITROGEN VALUES RECORDED 3/2/82.

LATTICE BLOCK LOT

```
                  LATTICE BLOCK LOT LOCATED AT SYMPHONY SQUARE AUSTIN
                STORM DATE =   MAR,11,82
                STORM NO. =          2  NUMBER OF SAMPLES =         6
SA     Q        TKN          NO3         TN          COD         TSS          ZN          PB          TIME
NO    CFS      MG/L         MG/L        MG/L        MG/L        MG/L         MG/L        MG/L         MIN
              10**-2       10**-2      10**-2      10**-2      10**-2       10**-2      10**-2
 1   0.000       0.0          0.0         0.0         0.0          0.0         0.0         0.0         0.0

 2   0.039    225.0         69.0       294.0      7360.0       7200.0         3.1         2.4         3.0

 3   0.063    180.0         66.0       246.0      4110.0       2880.0         2.0         0.0         8.0

 4   0.078    210.0         60.0       270.0      2670.0       2500.0         2.4         2.8        23.0

 5   0.045    142.0         58.0       200.0      3390.0        780.0         2.0         0.8        45.0

 6   0.018    127.0         56.0       183.0      4290.0       1220.0         2.0         0.8        53.0
               TOTAL FLOW AND POLLUTANTS.
               **********************************

   VO         STKN       SNO3         STN          SCOD          STSS           SZN           SPB
  CU.FT         LB         LB          LB            LB            LB            LB            LB
  10**1    10**-5     10**-5      10**-5        10**-5        10**-5        10**-5        10**-5
  0.00         0.0        0.0         0.0           0.0            0.0         0.000         0.000

  0.35        49.4       15.1        64.5        1614.6         1579.5         0.680         0.522

  1.88       221.5       78.2       299.7        5544.8         4333.5         2.593         0.570

  8.23      1054.3      316.2      1370.5       16133.0        14247.6        12.110        11.872

 16.34      1774.7      610.5      2385.2       33333.0        18205.1        22.258        16.185

 17.86      1894.8      663.4      2558.1       37387.1        19358.0        24.148        16.912
               RUNOFF AND POLLUTANT PER UNIT AREA.
               ****************************************

   VO        TKN        NO3          TN           COD           TSS         ZN           PB
   IN       LB/AC      LB/AC        LB/AC        LB/AC         LB/AC       LB/AC        LB/AC
           10**-5     10**-5       10**-5         10**-5      10**-5      10**-5        10**-5
  0.34    13250.0     4639.0      17889.1      261448.0      135370.5    168.864      118.268
               AVERAGE POLLUTANTS IN THE SAMPLE.
               *********************************

 TKN          NO3           TN          COD           TSS           ZN           PB
 MG/L         MG/L          MG/L        MG/L          MG/L          MG/L         MG/L
10**-2       10**-2        10**-2      10**-2        10**-2        10**-2       10**-2
 170.0          59.5        229.5      3354.0        1736.6           2.2          1.5
```

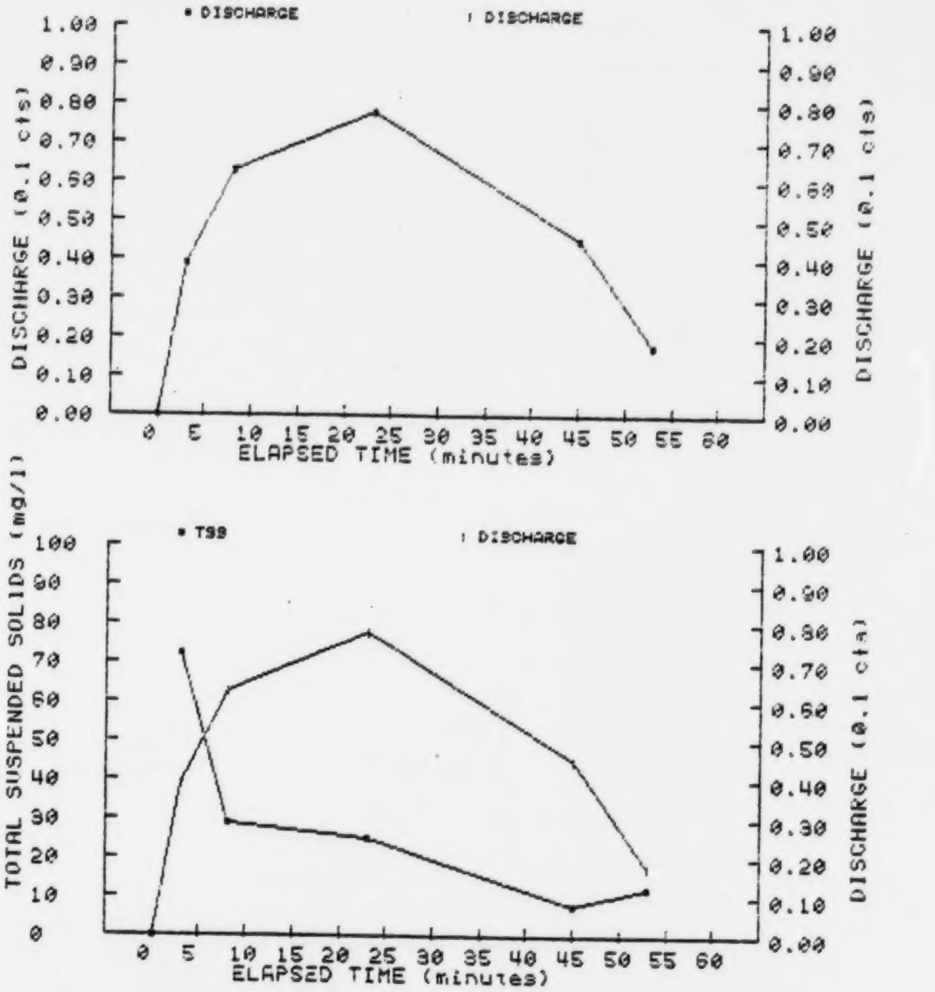


FIG. C-13 DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/11/82
LATTICE BLOCK LOT

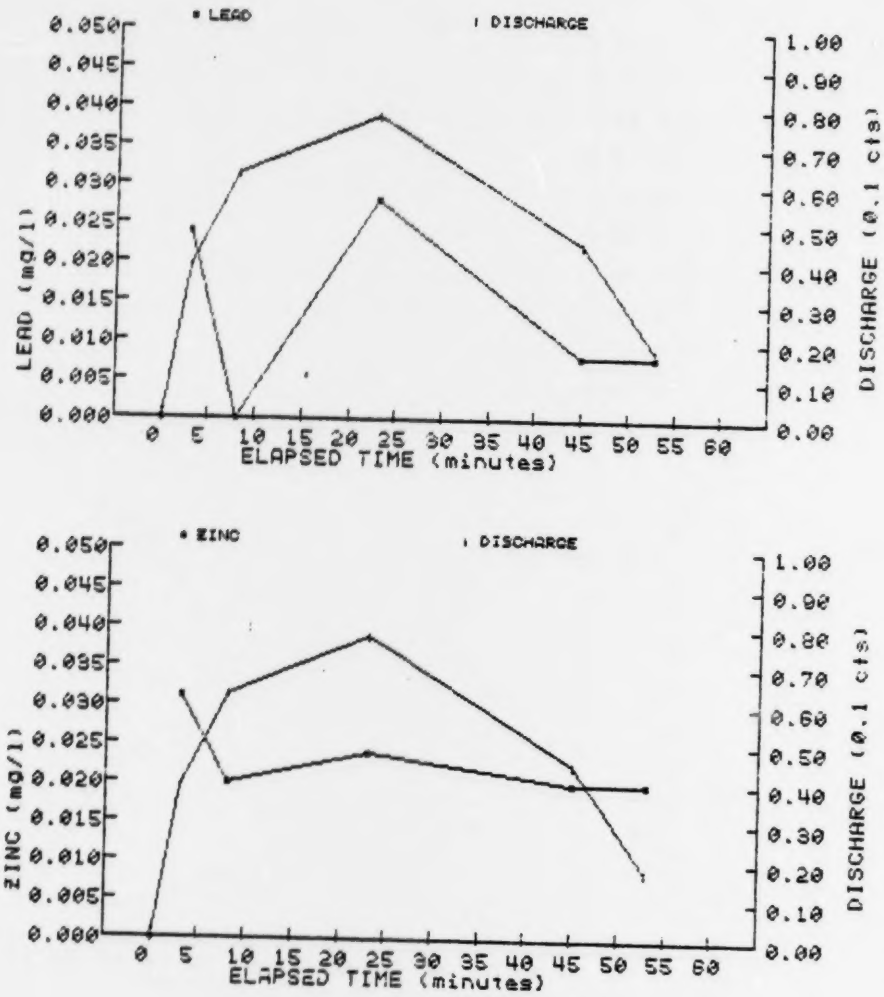


FIG. C-14. LEAD AND ZINC VALUES RECORDED 3/11/82.

LATTICE BLOCK LOT

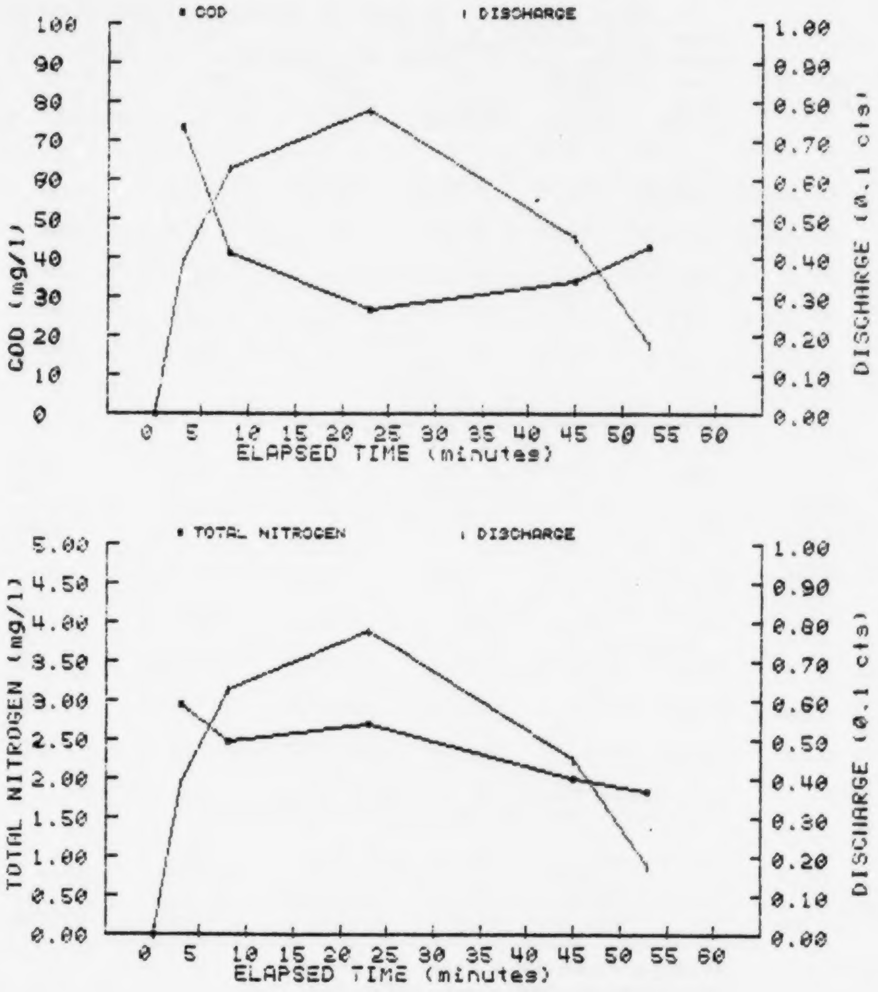


FIG. C-15. COD AND TOTAL NITROGEN VALUES RECORDED 3/11/82.

LATTICE BLOCK LOT

```
          LATTICE BLOCK LOT LOCATED AT SYMPHONY SQUARE AUSTIN
        STORM DATE =    MAR,18,82
        STORM NO. =          3  NUMBER OF SAMPLES =        6
SA    Q      TKN       NO3       TN        COD       TSS        ZN        PB        TIME
NO   CFS    MG/L      MG/L      MG/L      MG/L      MG/L       MG/L      MG/L       MIN
           10**-2    10**-2    10**-2    10**-2    10**-2     10**-2    10**-2
 1  0.000     0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0

 2  0.000   387.0      46.0     433.0    8960.0   21200.0       4.1       1.3      12.0

 3  0.045   241.0      32.0     273.0    5980.0    3060.0       0.5       0.3      22.0

 4  0.113   183.0      31.0     214.0    4320.0    4260.0       0.5       1.1      34.0

 5  0.034   157.0      30.0     187.0    4140.0     930.0       2.0       1.6      38.0

 6  0.018   126.0      29.0     155.0    3770.0     680.0       0.5       1.0      47.0
        TOTAL FLOW AND POLLUTANTS.
        *********************************

  VO       STKN     SNO3        STN       SCOD       STSS          SZN         SPB
 CU.FT      LB        LB         LB         LB         LB           LB          LB
 10**1   10**-5   10**-5     10**-5     10**-5     10**-5       10**-5     10**-5
 0.00       0.0      0.0        0.0        0.0        0.0        0.000       0.000

 0.00       0.0      0.0        0.0        0.0        0.0        0.000       0.000

 1.35     203.3     27.0      230.3     5045.6     2581.9        0.422       0.253

 7.04     853.9    137.2      991.1    20403.2    17726.2        2.199       4.164

 8.80    1027.0    170.3     1197.3    24967.6    18751.5        4.404       5.928

10.21    1137.6    195.7     1333.3    28275.7    19348.2        4.843       6.770
        RUNOFF AND POLLUTANT PER UNIT AREA.
        *****************************************

  VO     TKN      NO3        TN         COD        TSS         ZN         PB
  IN    LB/AC    LB/AC     LB/AC     LB/AC       LB/AC      LB/AC      LB/AC
        10**-5   10**-5    10**-5     10**-5     10**-5     10**-5      10**-5
 0.20   7955.0   1368.0    9323.7   197732.4   135302.0     33.868      47.343
        AVERAGE POLLUTANTS IN THE SAMPLE.
        *********************************

TKN        NO3        TN        COD        TSS        ZN        PB
MG/L       MG/L       MG/L      MG/L       MG/L       MG/L      MG/L
10**-2     10**-2     10**-2    10**-2     10**-2     10**-2    10**-2
 178.5       30.7      209.3    4437.9     3036.7       0.8       1.1
```

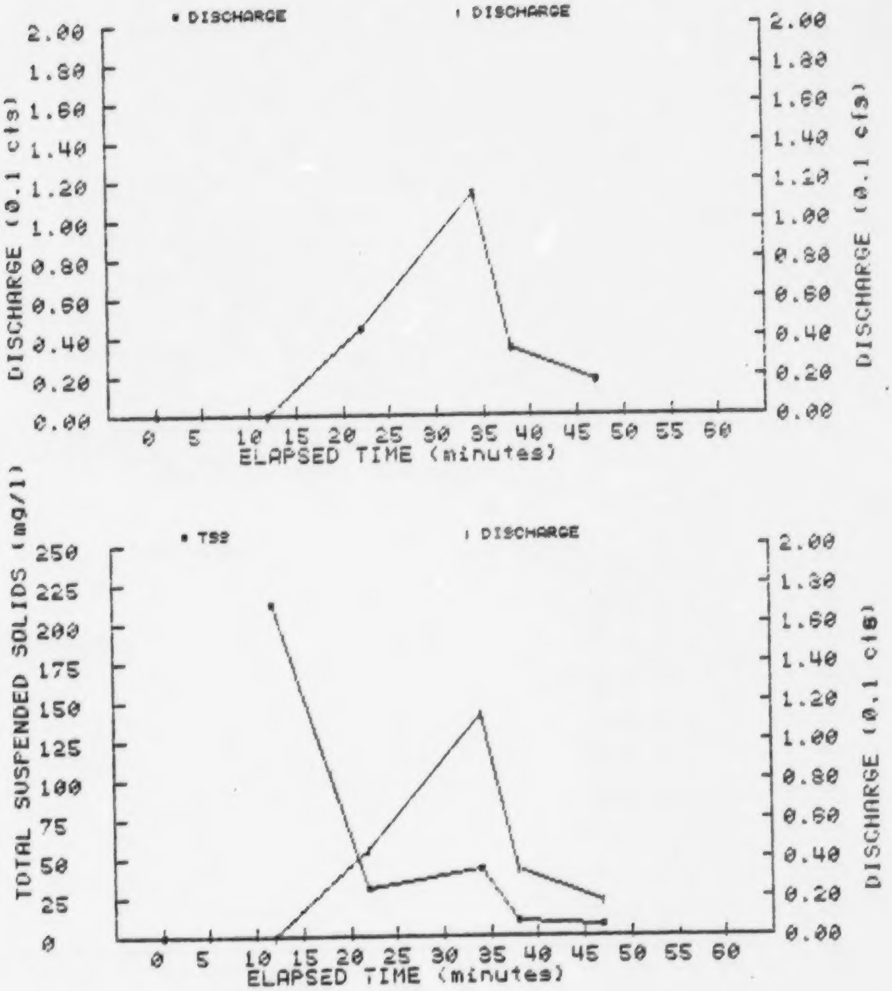


FIG. C-16. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/18/82

LATTICE BLOCK LOT

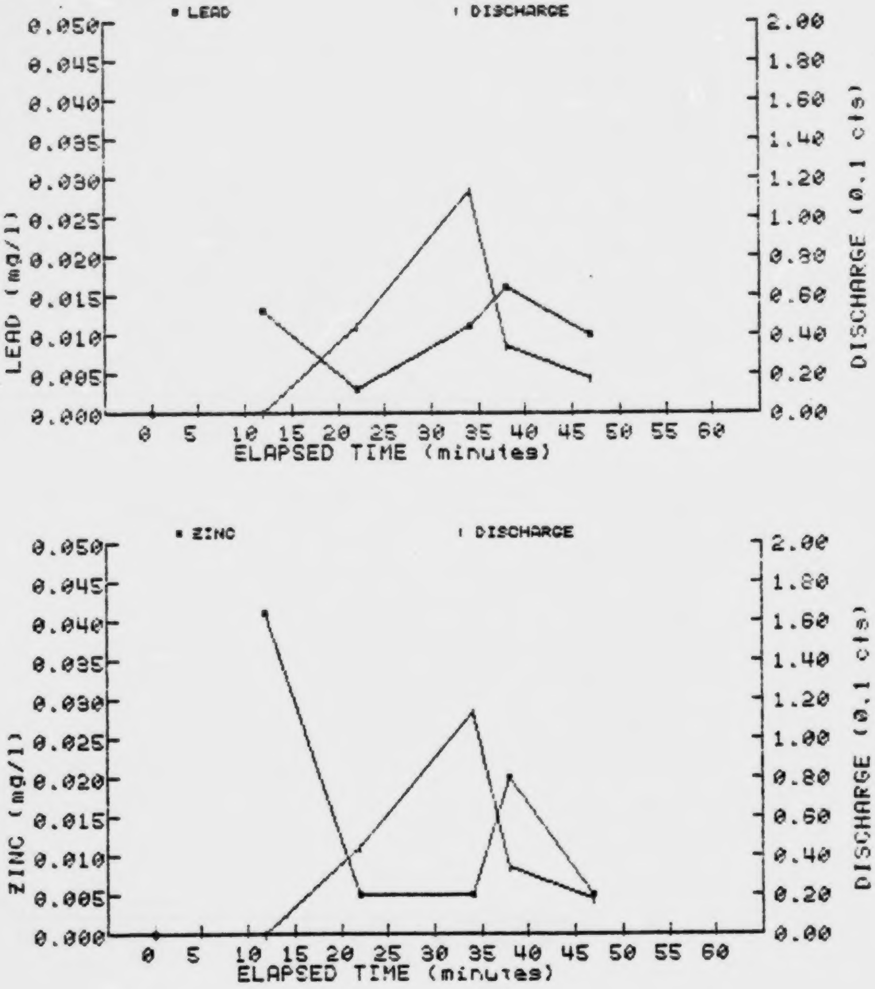


FIG. C-17. LEAD AND ZINC VALUES RECORDED 3/18/82.

LATTICE BLOCK LOT

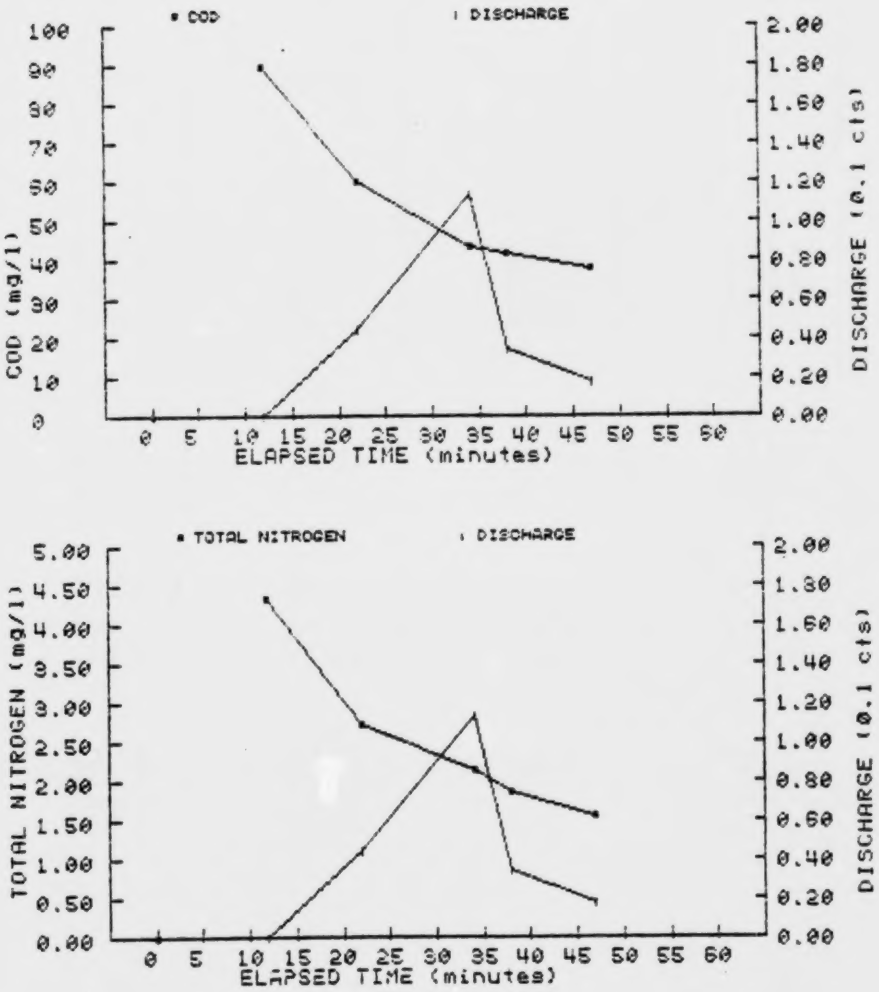


FIG.C-18. COD AND TOTAL NITROGEN VALUES RECORDED 3/18/82.

LATTICE BLOCK LOT

TSS

```
EQUATION                       A          B         R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.09086    0.03127    0.40183      0.07136           15
Y = A(EXP(BX))             0.00872    0.02590    0.35452      0.23976           15
Y = A(X**B)                0.00974    0.61326    0.98664      0.04020           15
Y = A + BX                 0.03828    0.00129    0.72828      0.04810           15
```

COD

```
EQUATION                       A          B         R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.10355    0.03854    0.32109      0.10480           15
Y = A(EXP(BX))             0.00774    0.02851    0.41019      0.29652           15
Y = A(X**B)                0.01004    0.62550    0.98046      0.05965           15
Y = A + BX                 0.01190    0.00197    0.89677      0.04087           15
```

TN

```
EQUATION                       A          B         R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.00614    0.00239    0.28529      0.00709           15
Y = A(EXP(BX))             0.00058    0.02674    0.58667      0.01425           15
Y = A(X**B)                0.00103    0.46555    0.88332      0.00589           15
Y = A + BX                -0.00023    0.00013    0.92651      0.00227           15
```

Pb

```
EQUATION                       A          B         R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.00319    0.00139    0.17531      0.00564           15
Y = A(EXP(BX))             0.00010    0.03412    0.69979      0.00897           15
Y = A(X**B)                0.00034    0.42189    0.53115      0.00642           15
Y = A + BX                -0.00137    0.00009    0.76792      0.00299           15
```

Zn

```
EQUATION                       A          B         R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.00684    0.00251    0.23534      0.00845           15
Y = A(EXP(BX))             0.00054    0.02653    0.52640      0.01371           15
Y = A(X**B)                0.00098    0.45851    0.78044      0.00846           15
Y = A + BX                 0.00099    0.00013    0.64180      0.00578           15
```

```
               ASPHALT LOT WITH GRAVEL TRENCH LOCATED AT THE AUSTIN AIRPORT
           STORM DATE =   MAR,03,82
           STORM NO. =        1  NUMBER OF SAMPLES =       6
SA    Q      TKN       NO3       TN        COD        TSS         ZN         PB        TIME
NO   CFS    MG/L      MG/L      MG/L      MG/L       MG/L        MG/L       MG/L       MIN
           10**-2    10**-2    10**-2    10**-2     10**-2      10**-2     10**-2
 1  0.000     0.0       0.0       0.0       0.0        0.0         0.0        0.0        0.0

 2  0.269   149.0     114.0     263.0    8580.0    25900.0         9.9        1.8        3.0

 3  0.369   126.0      49.0     175.0    6460.0    20700.0         4.1        3.2       18.0

 4  0.440   164.0      58.0     222.0    4520.0    20800.0         9.2        3.6       33.0

 5  0.341    43.0      20.0      63.0    2400.0     5000.0         4.5        1.7       48.0

 6  0.369   104.0      20.0     124.0    2790.0     3900.0         2.7        2.1       73.0

           TOTAL FLOW AND POLLUTANTS.
           ************************************

  VO        STKN      SN03        STN        SCOD        STSS          SZN         SPB
 CU.FT        LB        LB         LB          LB          LB           LB          LB
 10**1    10**-5    10**-5     10**-5      10**-5      10**-5       10**-5      10**-5
 0.00        0.0       0.0        0.0         0.0         0.0        0.000       0.000

 2.42      225.5     172.5      398.0     12982.6     39189.9       14.980       2.693

31.13     2486.4    1051.7     3538.1    128899.2    410625.4       88.549      59.396

67.54     6217.9    2371.4     8589.3    231743.3    883890.4      297.878     140.852

02.68     7162.4    2810.7     9973.1    284460.8    993718.4      396.723     178.193

55.93    10623.6    3476.4    14100.0    377315.4   1123515.0      486.583     247.418

           RUNOFF AND POLLUTANT PER UNIT AREA.
           **********************************************

  VO        TKN       NO3         TN         COD         TSS          ZN          PB
  IN       LB/AC     LB/AC      LB/AC       LB/AC       LB/AC        LB/AC       LB/AC
          10**-5    10**-5     10**-5      10**-5      10**-5       10**-5      10**-5
 0.31     7788.6    2548.0    10337.2    276624.2    823691.4      356.732     181.392

           AVERAGE POLLUTANTS IN THE SAMPLE.
           ************************************

 TKN        NO3          TN          COD          TSS          ZN          PB
 MG/L       MG/L        MG/L        MG/L         MG/L         MG/L        MG/L
10**-2     10**-2      10**-2      10**-2       10**-2       10**-2      10**-2
 109.1        35.7       144.8      3876.1      11541.7          5.0         2.5
```

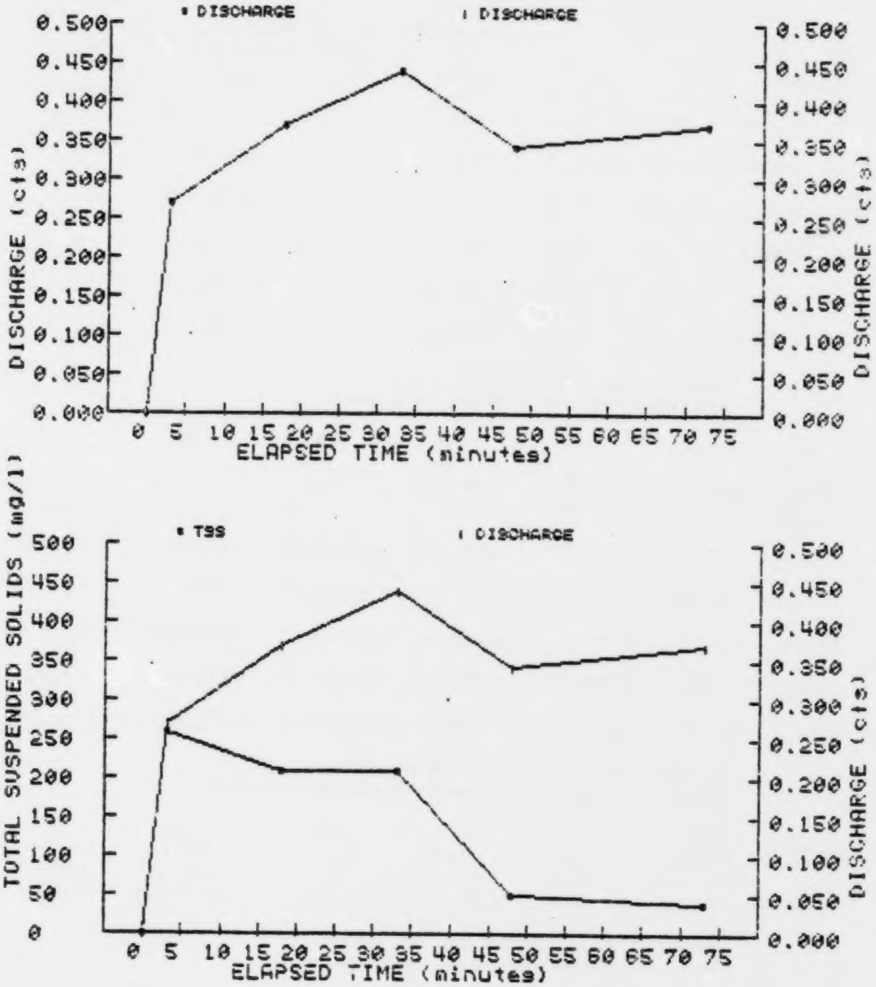


FIG. C-19.. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/3/82.

GRAVEL TRENCH LOT

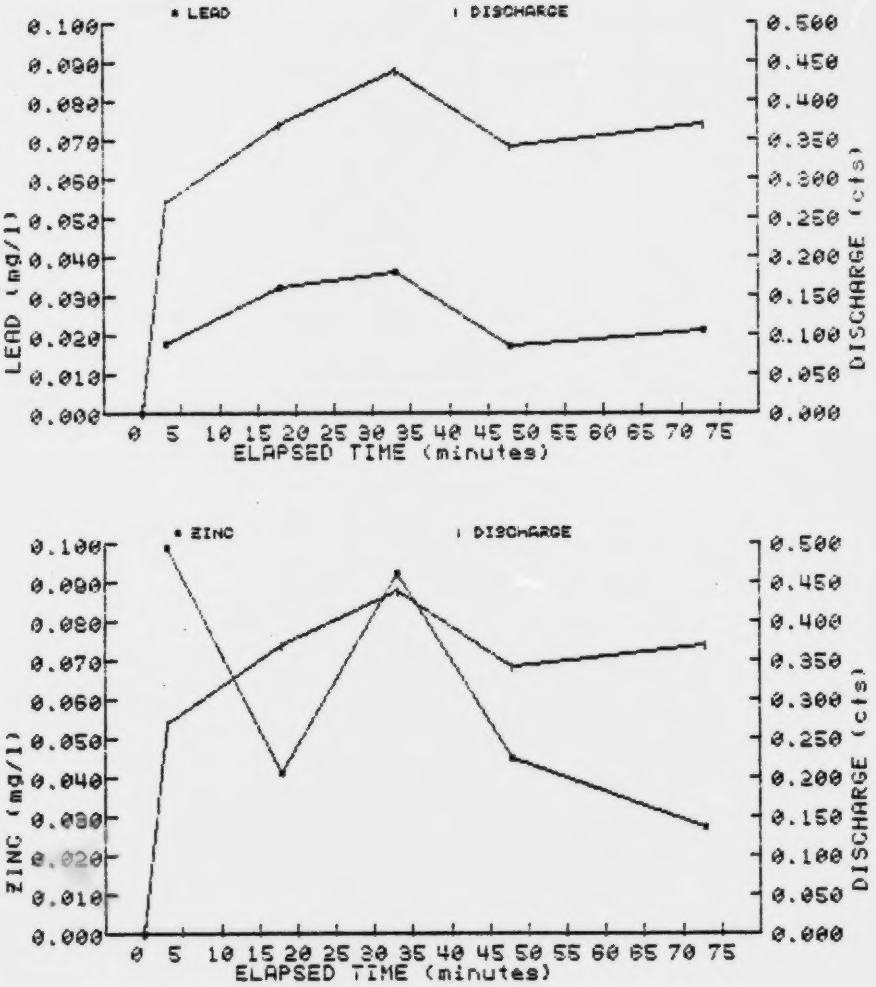


FIG. C-20. LEAD AND ZINC VALUES RECORDED 3/3/82.

GRAVEL TRENCH LOT

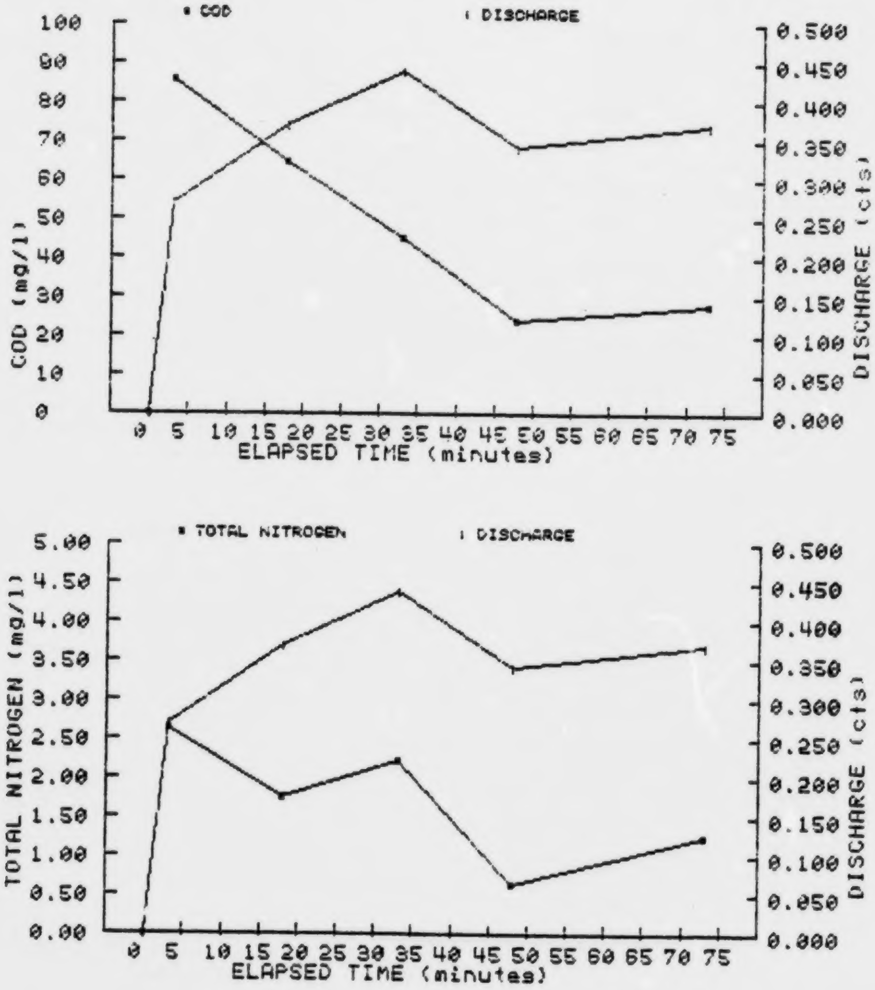


FIG.C-21. COD AND TOTAL NITROGEN VALUES RECORDED 3/3/82.

GRAVEL TRENCH LOT

```
             ASPHALT LOT WITH GRAVEL TRENCH LOCATED AT THE AUSTIN AIRPORT
         STORM DATE =   MAR,18,82
         STORM NO. =        2  NUMBER OF SAMPLES =        6
SA    Q     TKN      NO3       TN       COD       TSS       ZN       PB     TIME
NO   CFS    MG/L     MG/L     MG/L      MG/L      MG/L     MG/L     MG/L      MIN
          10**-2   10**-2   10**-2    10**-2    10**-2   10**-2   10**-2
 1  0.000    0.0     0.0      0.0       0.0       0.0      0.0      0.0      0.0

 2  0.115  262.0   174.0    436.0   16900.0   83600.0     18.8      3.0      2.0

 3  0.538  231.0    91.0    322.0   20200.0   79300.0     27.4      5.8     42.0

 4  0.580  105.0    61.0    166.0    5000.0   15400.0      5.6      3.1     57.0

 5  0.341   74.0    58.0    132.0    2710.0    4290.0      1.6      2.3     67.0

 6  0.185   74.0    44.0    118.0    2300.0    1960.0      2.0      2.7     77.0

         TOTAL FLOW AND POLLUTANTS.
         *********************************

  VO      STKN    SNO3       STN       SCOD       STSS       SZN       SPB
CU.FT       LB      LB        LB         LB         LB        LB        LB
10**1  10**-5  10**-5    10**-5     10**-5     10**-5    10**-5    10**-5
 0.00      0.0     0.0       0.0        0.0        0.0     0.000     0.000

 0.69    113.0    75.0     188.0     7288.1    36052.5     8.107     1.302

79.05  11426.2  4531.8   15958.0   996582.9  3919769.0    1350.0   284.378

29.36  14727.8  6449.8   21177.6  1153801.5  4404002.0    1526.1   382.482

56.99  16005.7  7451.4   23457.1  1200599.8  4478084.0    1553.7   421.682

72.77  16735.5  7885.4   24620.9  1223283.3  4497414.0    1573.4   448.311

          RUNOFF AND POLLUTANT PER UNIT AREA.
          ****************************************

  VO     TKN     NO3       TN       COD        TSS       ZN       PB
  IN   LB/AC   LB/AC    LB/AC    LB/AC      LB/AC    LB/AC    LB/AC
       10**-5  10**-5   10**-5    10**-5     10**-5   10**-5    10**-5
 0.35 12269.4  5781.0  18050.5  896835.3  3297224.5   1153.5  328.674

          AVERAGE POLLUTANTS IN THE SAMPLE.
          ********************************

 TKN      NO3       TN       COD       TSS      ZN       PB
 MG/L     MG/L     MG/L     MG/L      MG/L     MG/L     MG/L
10**-2   10**-2   10**-2   10**-2    10**-2   10**-2   10**-2
 155.2     73.1    228.3  11341.8   41698.2     14.6      4.2
```

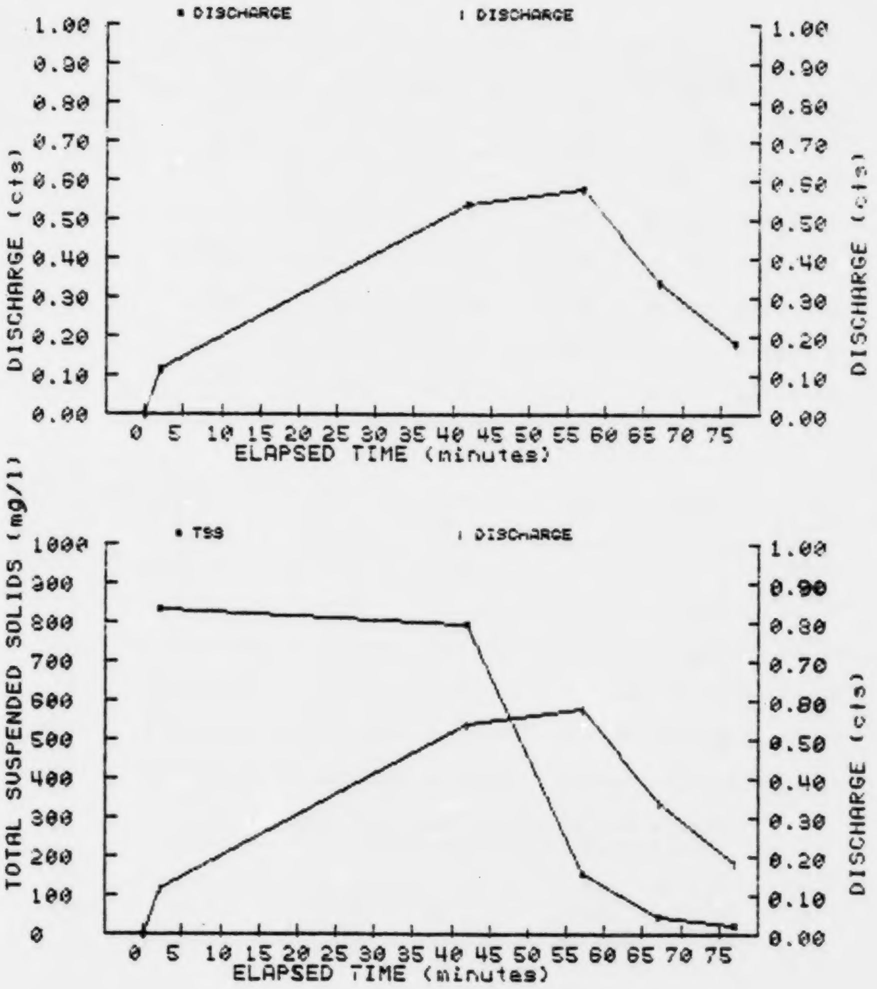


FIG. C-22. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/18/82

GRAVEL TRENCH LOT

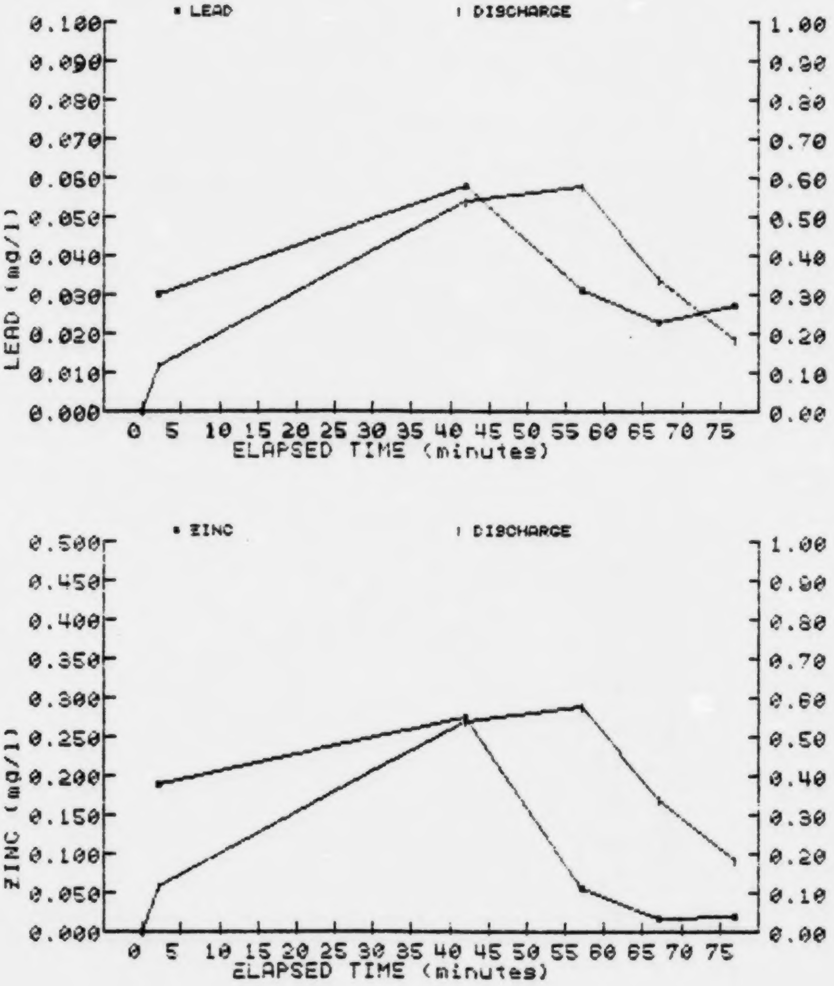


FIG. C-23. LEAD AND ZINC VALUES RECORDED 3/18/82.

GRAVEL TRENCH LOT

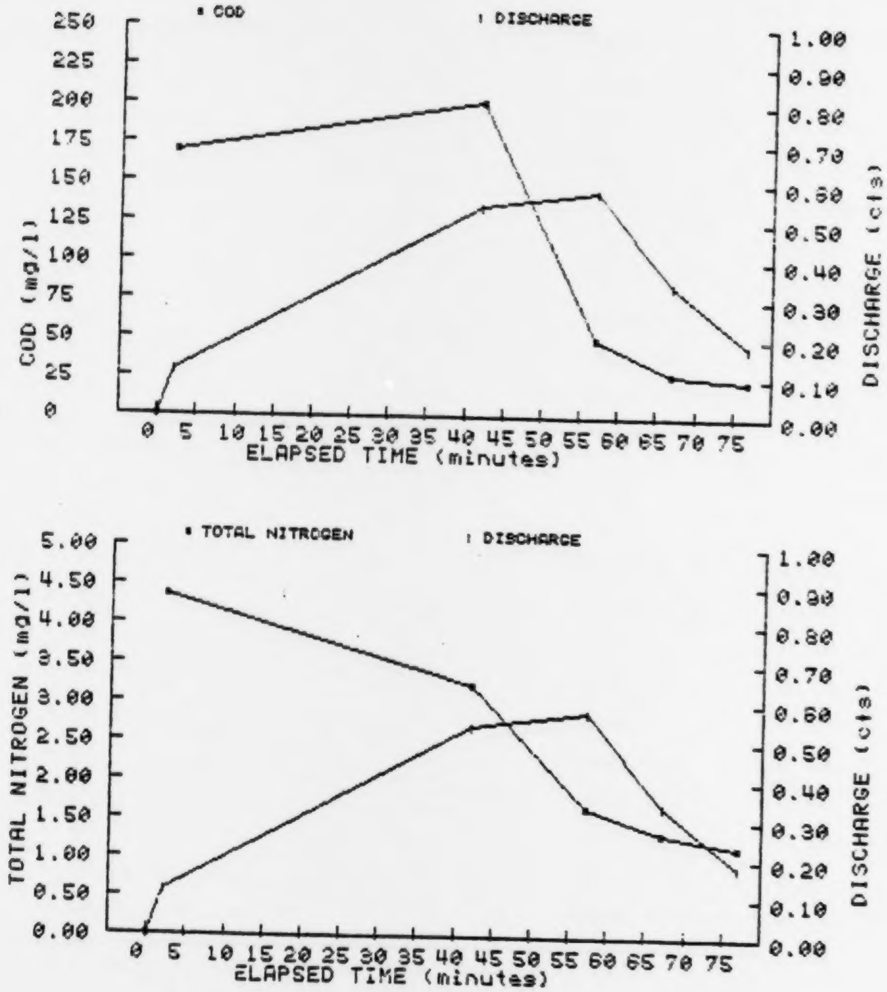


FIG.C-24. COD AND TOTAL NITROGEN VALUES RECORDED 3/18/82.

GRAVEL TRENCH LOT

```
            ASPHALT LOT WITH GRAVEL TRENCH LOCATED AT THE AUSTIN AIRPORT
        STORM DATE =    APR,04,82
        STORM NO. =         3  NUMBER OF SAMPLES =        6
SA    Q     TKN       NO3        TN        COD        TSS        ZN        PB       TIME
NO   CFS    MG/L      MG/L      MG/L       MG/L       MG/L      MG/L      MG/L      MIN
          10**-2    10**-2    10**-2     10**-2     10**-2    10**-2    10**-2
 1  0.000     0.0       0.0       0.0        0.0        0.0       0.0       0.0       0.0

 2  0.185   452.0     212.0     664.0    43400.0   191300.0      39.3       4.0      16.0

 3  0.411   203.0      81.0     284.0     8830.0    18500.0       8.8       0.4      36.0

 4  1.667   133.0      52.0     185.0     7220.0    13800.0       7.4       1.1      55.0

 5  0.411   107.0      40.0     147.0     3000.0     7900.0       2.7       1.6      61.0

 6  0.000   159.0      58.0     217.0     3200.0     1910.0       2.7       0.9      84.0
        TOTAL FLOW AND POLLUTANTS.
        **********************************

  VO       STKN     SNO3       STN       SCOD       STSS         SZN        SPB
 CU.FT      LB       LB         LB         LB         LB          LB         LB
 10**1   10**-5   10**-5     10**-5     10**-5     10**-5      10**-5   10**-5
 0.00       0.0      0.0        0.0        0.0         0.0      0.000      0.000

 8.88    2508.6   1176.6     3685.2   240869.9   1061714.8    218.115     22.144

44.64    7045.6   2986.9    10032.6   438220.4   1475189.5    414.795     31.531

63.09   16891.5   6836.4    23727.9   972707.8   2496786.0    962.607    112.963

00.49   19392.9   7771.5    27164.4  1042840.1   2681468.0     1025.7    150.835

28.85   22211.0   8799.6    31010.6  1099558.0   2715321.5     1073.5    167.318
        RUNOFF AND POLLUTANT PER UNIT AREA.
        ****************************************

  VO      TKN      NO3        TN         COD         TSS         ZN         PB
  IN     LB/AC    LB/AC      LB/AC      LB/AC       LB/AC      LB/AC      LB/AC
         10**-5   10**-5     10**-5      10**-5     10**-5     10**-5      10**-5
 0.46   16283.7   6451.0    22735.0    806127.6   1990705.0    787.084    122.667
        AVERAGE POLLUTANTS IN THE SAMPLE.
        **********************************

 TKN        NO3        TN        COD         TSS        ZN        PB
 MG/L       MG/L       MG/L      MG/L        MG/L       MG/L      MG/L
10**-2     10**-2     10**-2    10**-2      10**-2     10**-2    10**-2
 155.5        61.6     217.1    7696.5     19006.2        7.5       1.2
```

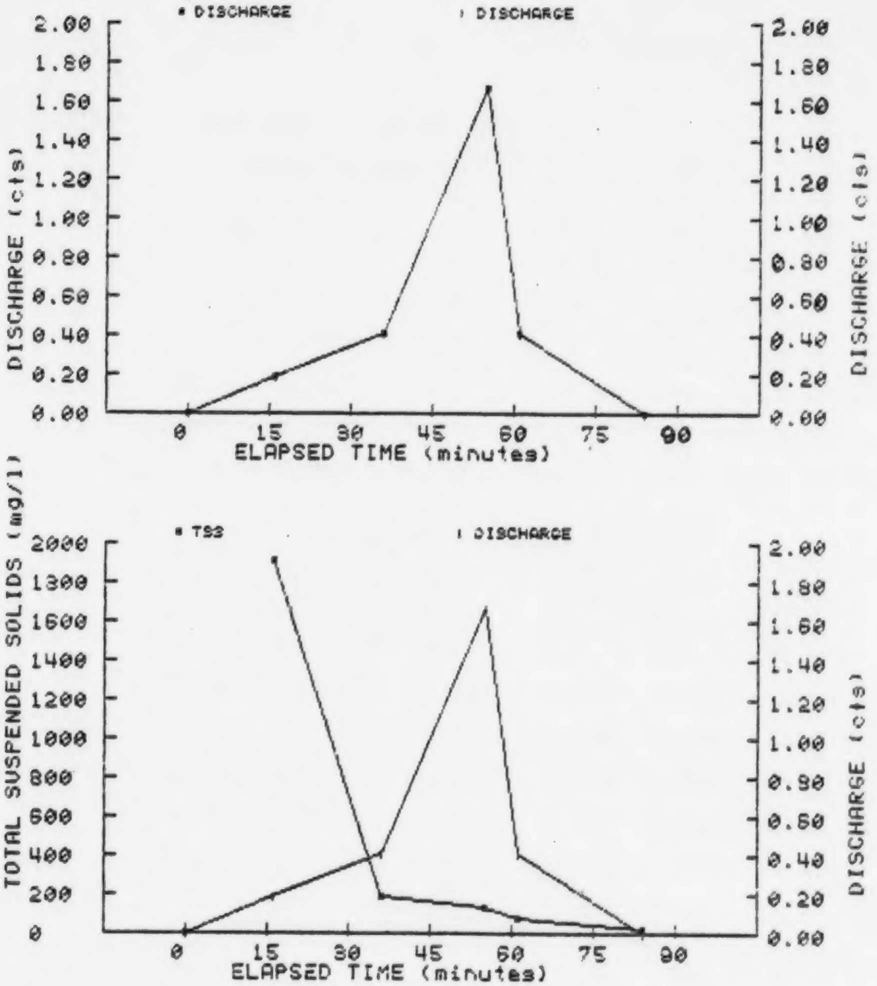


FIG. C-25. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 4/4/82.

GRAVEL TRENCH LOT

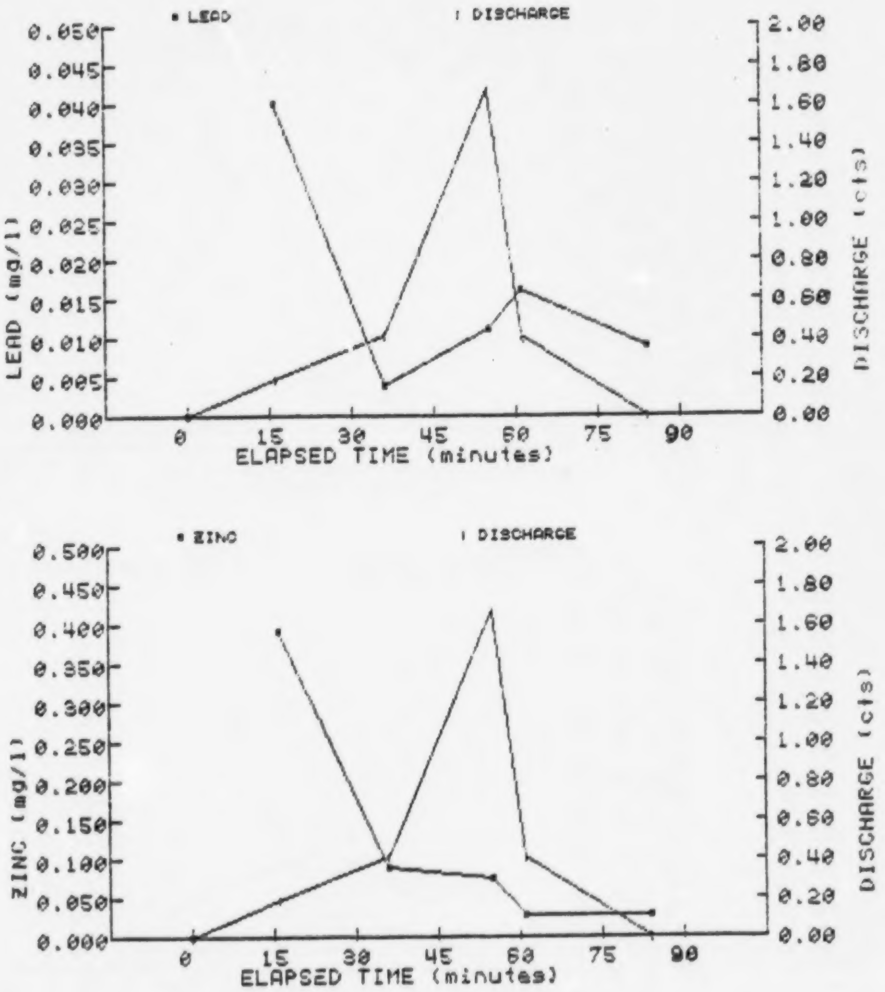


FIG. C-26. LEAD AND ZINC VALUES RECORDED 4/4/82.

GRAVEL TRENCH LOT

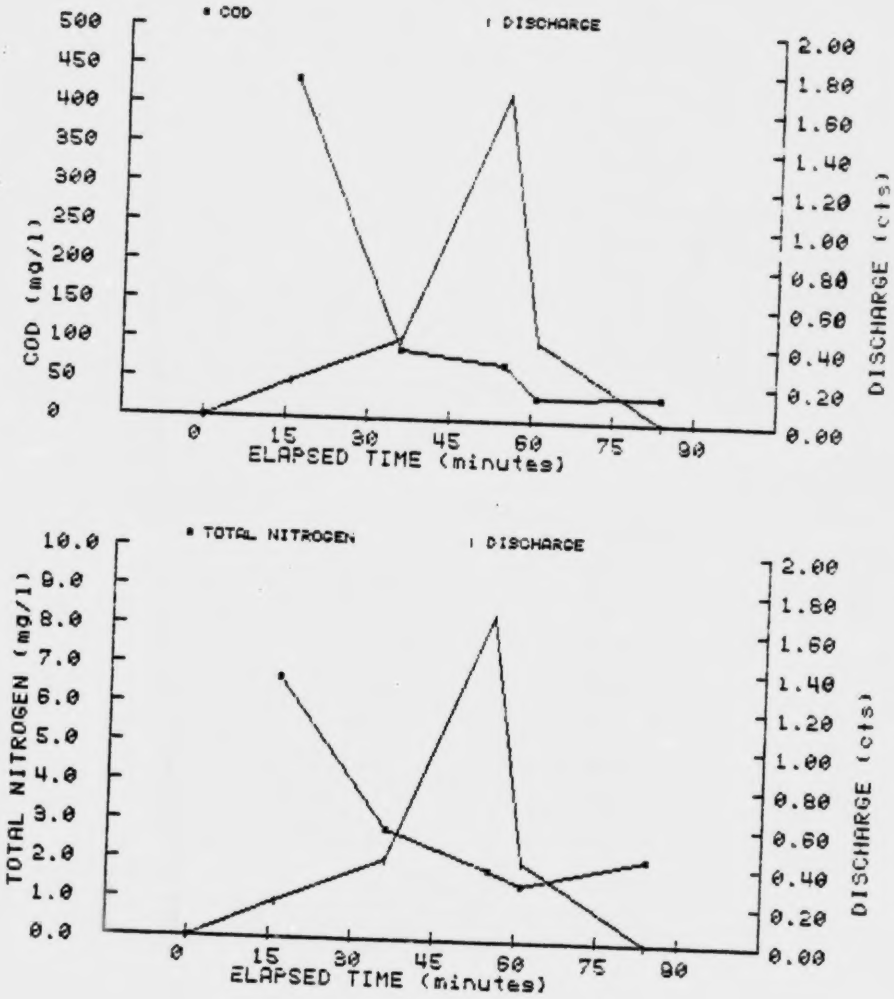


FIG.C-27. COD AND TOTAL NITROGEN VALUES RECORDED 4/4/82.

GRAVEL TRENCH LOT

TSS

```
EQUATION                        A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))           10.23323    4.16193    0.26631      14.73630           16
Y = A(EXP(BX))               0.31313    0.00281    0.32868      49.49708           16
Y = A(X**B)                  0.08275    0.78702    0.97023      12.33353           16
Y = A + BX                   5.16745    0.01486    0.47959      12.41099           16
```

COD

```
EQUATION                        A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))            2.99437    1.29543    0.30431       4.17830           16
Y = A(EXP(BX))               0.09804    0.00282    0.38140      14.98037           16
Y = A(X**B)                  0.03442    0.73436    0.97032       2.98004           16
Y = A + BX                   0.86126    0.00520    0.69311       2.77514           16
```

TN

```
EQUATION                        A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))            0.06797    0.03053    0.35738       0.08732           16
Y = A(EXP(BX))               0.00438    0.00245    0.49321       0.25469           16
Y = A(X**B)                  0.00273    0.55207    0.94324       0.05920           16
Y = A + BX                   0.01015    0.00013    0.92127       0.03056           16
```

Pb

```
EQUATION                        A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))            0.00084    0.00036    0.24383       0.00137           16
Y = A(EXP(BX))               0.00009    0.00242    0.59024       0.00255           16
Y = A(X**B)                  0.00011    0.33841    0.62018       0.00147           16
Y = A + BX                   0.00041    0.00000    0.43281       0.00119           16
```

Zn

```
EQUATION                        A          B        R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))            0.00349    0.00152    0.27492       0.00525           16
Y = A(EXP(BX))               0.00032    0.00214    0.58141       0.01053           16
Y = A(X**B)                  0.00032    0.40206    0.76935       0.00526           16
Y = A + BX                   0.00122    0.00001    0.57893       0.00400           16
```

SENIOR CITIZEN'S CENTER PARKING LOT-AUSTIN, TEXAS

```
           STORM DATE =   JUN,03,81
           STORM NO. =        2  NUMBER OF SAMPLES =       11
SA    Q      PB      CU      ZN      CD      TSS       VSS      TKN      P       OIL      COD      COL    BOD5    TIM
NO  CFS     MG/L    MG/L    MG/L    MG/L    MG/L      MG/L     MG/L     MG/L    MG/L     MG/L     NO/CC  MG/L     MI
           10**-2  10**-2  10**-2  10**-2  10**-2    10**-2   10**-2   10**-2  10**-2   10**-2   10**-2 10**-2
1 .00000     0.0     0.0     0.0     0.0      0.0       0.0      0.0     0.0      0.0      0.0     0.0     0.0    0
2 .00010     3.9     0.0     0.8     0.0   2160.0    1050.0     78.0     3.4     17.0  10300.0   43000  1980.0    5
3 .00020     3.0     0.0     1.3     0.0   4390.0    1810.0    126.0     1.3     34.0   8880.0   39000   970.0   20
4 .00050     3.6     0.0     1.3     0.0   3940.0    1360.0     50.0     4.3     16.0   8880.0   11000   470.0   25
5 .00600     3.0     0.0     0.8     0.0   2800.0    1060.0     12.0     4.3     11.0   6700.0   39000   530.0   30
6 .00600     3.0     0.0     0.8     0.0  14400.0    3390.0     61.0     5.7     29.0   8090.0   72000    85.0   35
7 .34000     5.7     0.0     1.2     0.0   9750.0    3770.0    126.0     2.5    202.0   4110.0   42000   770.0   40
8 .84000     0.0     0.0     0.0     0.0   6975.0    2695.0    110.0     2.7    100.0   3000.0   34000   500.0   43
9 .44000     0.3     0.0     0.8     0.0   4200.0    1620.0     79.0     2.9      5.0   1720.0   27000   260.0   45
0 .08000     0.3     0.0     0.8     0.0    410.0     100.0     44.0     2.9      2.0    530.0   23000   240.0   55
1 .02000     0.5     0.0     0.8     0.0    650.0     200.0     84.0     4.3      5.0   2320.0   22000   360.0   65
           TOTAL FLOW AND POLLUTANTS.
           ******************************
  VO     SPB     SCU       SZN      SCD       STSS      SVSS      STKN      SP        SOIL      SCOD      SCOL   SBOD5
 CU.FT   LB      LB        LB       LB        LB        LB        LB        LB        LB        LB        NO     LB
 10**1                                                                                                10**10
  0.00 0.0000  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000 0.0000
  0.01 0.0000  0.0000    0.0000    0.0000    0.0002    0.0001    0.0000    0.0000    0.0000    0.0008    0.0001 0.0001
  0.06 0.0000  0.0000    0.0000    0.0000    0.0014    0.0006    0.0000    0.0000    0.0000    0.0033    0.0006 0.0004
  0.07 0.0000  0.0000    0.0000    0.0000    0.0017    0.0007    0.0000    0.0000    0.0000    0.0039    0.0007 0.0005
  0.16 0.0000  0.0000    0.0000    0.0000    0.0034    0.0013    0.0001    0.0000    0.0000    0.0079    0.0018 0.0008
  0.34 0.0000  0.0000    0.0000    0.0000    0.0196    0.0051    0.0001    0.0000    0.0001    0.0170    0.0054 0.0009
  5.53 0.0002  0.0000    0.0000    0.0000    0.3358    0.1274    0.0042    0.0001    0.0066    0.1504    0.0672 0.0258
 16.15 0.0002  0.0000    0.0000    0.0000    0.7988    0.3063    0.0115    0.0003    0.0132    0.3495    0.1695 0.0590
 23.83 0.0002  0.0000    0.0001    0.0000    1.0004    0.3841    0.0153    0.0004    0.0135    0.4320    0.2282 0.0715
 39.43 0.0002  0.0000    0.0002    0.0000    1.0404    0.3918    0.0215    0.0007    0.0137    0.4837    0.3299 0.0949
 42.43 0.0002  0.0000    0.0002    0.0000    1.0526    0.3976    0.0231    0.0008    0.0138    0.5272    0.3486 0.1017
           RUNOFF AND POLLUTANT PER UNIT AREA.
           ****************************************
  VO     PB      CU        ZN       CD        TSS       VSS       TKN       P         OIL       COD       COL    BOD5

  IN     LB/AC   LB/AC     LB/AC    LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     NO/AC  LB/A
                                                                                                         10**10
  0.46 0.0010  0.0000    0.0007    0.0000    4.1309    1.5603    0.0907    0.0030    0.0540    2.0691    1.3681 0.3990
           AVERAGE POLLUTANTS IN THE SAMPLE.
           ********************************

   PB       CU        ZN        CD        TSS       VSS       TKN      P         OIL       COD       COL       BOD5
  MG/L     MG/L      MG/L      MG/L      MG/L      MG/L      MG/L     MG/L      MG/L      MG/L      NO/CC     MG/L
 10**-2   10**-2    10**-2    10**-2    10**-2    10**-2    10**-2   10**-2    10**-2    10**-2    10**2     10**-2
    0.9      0.0       0.7       0.0    3973.2    1500.8      87.3       2.9      52.0    1990.2       2.9     383.8
```

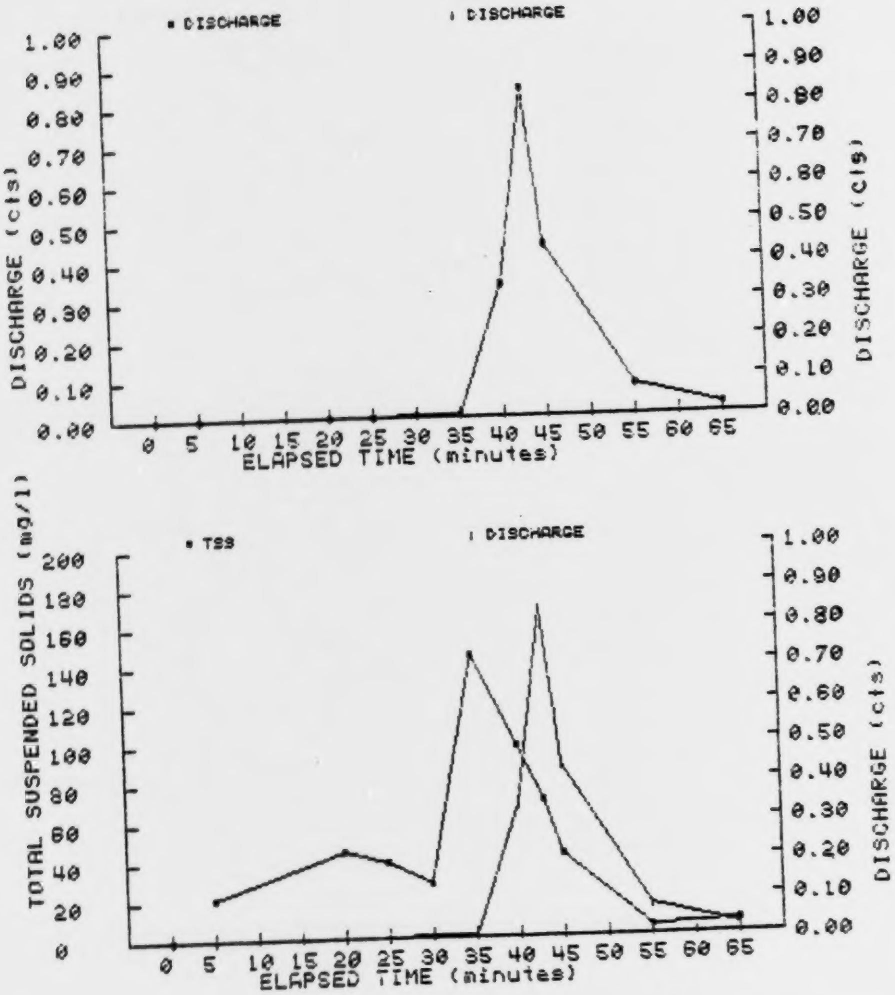
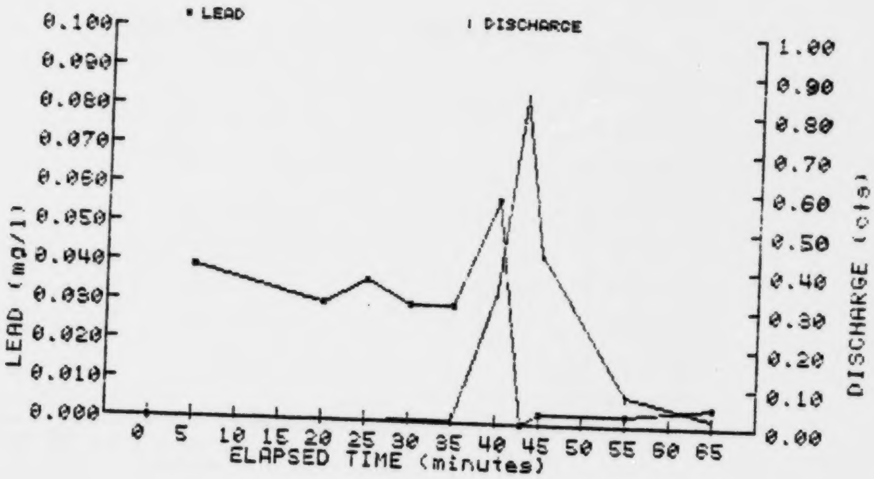


FIG. C-28. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 6/3/81.

CONVENTIONAL ASPHALT LOT



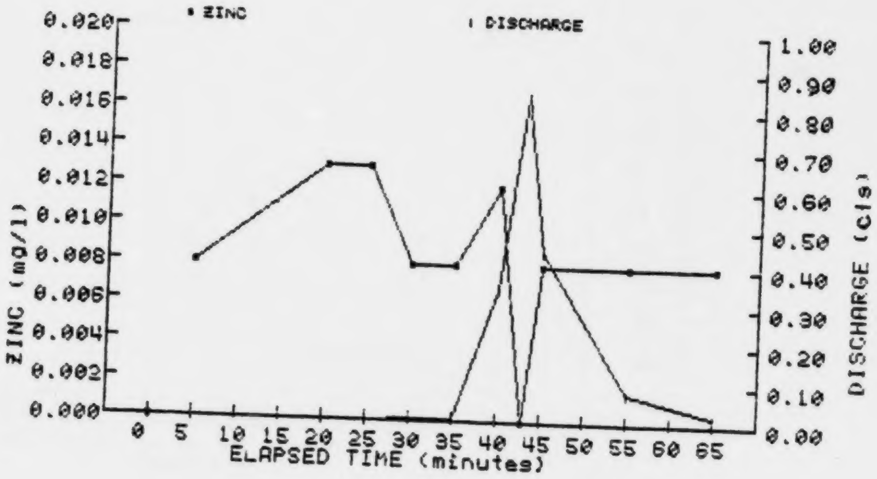


FIG.C-29. LEAD AND ZINC VALUES RECORDED 6/3/81.

CONVENTIONAL ASPHALT LOT

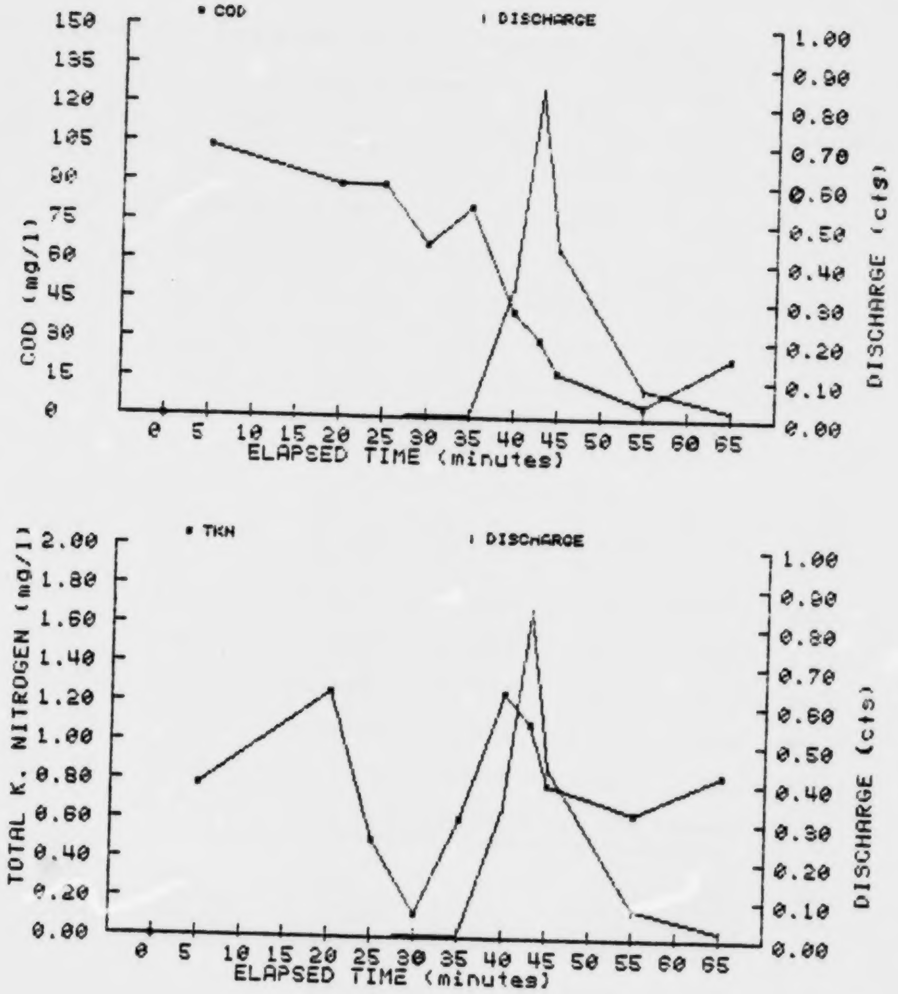


FIG. C-30. COD AND TKN VALUES RECORDED 6/3/81.

CONVENTIONAL ASPHALT LOT

```
          CONVENTIONAL ASPHALT LOT AT THE SENIOR CITIZENS ACTIVITY CENTER
        STORM DATE =    MAY,11,82
        STORM NO. =        3  NUMBER OF SAMPLES =        6
 SA    Q     TKN       NO3        TN        COD        TSS         ZN         PB        TIME
 NO   CFS   MG/L      MG/L       MG/L       MG/L       MG/L        MG/L       MG/L       MIN
           10**-2    10**-2     10**-2     10**-2     10**-2     10**-2     10**-2
  1  0.000    0.0       0.0        0.0        0.0        0.0        0.0        0.0        0.0

  2  0.040  666.0     141.0      807.0    52770.0    44500.0        3.1        3.4        2.0

  3  0.194  782.0      60.0      846.0     9470.0    19800.0        3.8        1.7        5.0

  4  0.223  134.0      38.0      172.0     4970.0     2940.0        1.6        1.8        9.0

  5  0.051  121.0      58.0      179.0     3310.0     1040.0        3.8        1.9       15.0

  6  0.010  116.0      72.0      188.0     3550.0      330.0        0.5        2.8       25.0

        TOTAL FLOW AND POLLUTANTS.
        **********************************

   VO      STKN     SNO3       STN        SCOD        STSS         SZN        SPB
  CU.FT     LB        LB        LB          LB          LB          LB         LB
  10**1   10**-5   10**-5    10**-5      10**-5      10**-5      10**-5     10**-5
  0.00      0.0      0.0       0.0         0.0         0.0       0.000      0.000

  0.24     99.9     21.1     121.0      7915.5      6675.0       0.465      0.510

  2.35   1129.2    100.1    1234.6     20380.4     32736.7       5.467      2.800

  7.35   1548.3    219.0    1772.5     35924.1     41931.6      10.471      8.367

 12.28   1921.3    397.8    2324.3     46127.1     45137.4      22.184     14.347

 14.11   2053.9    480.1    2539.3     50187.4     45514.8      22.756     17.596

        RUNOFF AND POLLUTANT PER UNIT AREA.
        *****************************************

   VO      TKN      NO3        TN        COD          TSS         ZN         PB
   IN     LB/AC    LB/AC     LB/AC     LB/AC        LB/AC       LB/AC      LB/AC
          10**-5   10**-5    10**-5      10**-5      10**-5     10**-5      10**-5
  0.15   8054.7   1882.0    9958.1    196813.4    178489.4     89.240     69.002

        AVERAGE POLLUTANTS IN THE SAMPLE.
        *********************************

 TKN        NO3        TN        COD         TSS         ZN         PB
 MG/L       MG/L       MG/L      MG/L        MG/L        MG/L       MG/L
10**-2     10**-2     10**-2    10**-2      10**-2      10**-2     10**-2
 233.1       54.5      288.2    5696.8      5166.4         2.6        2.0
```

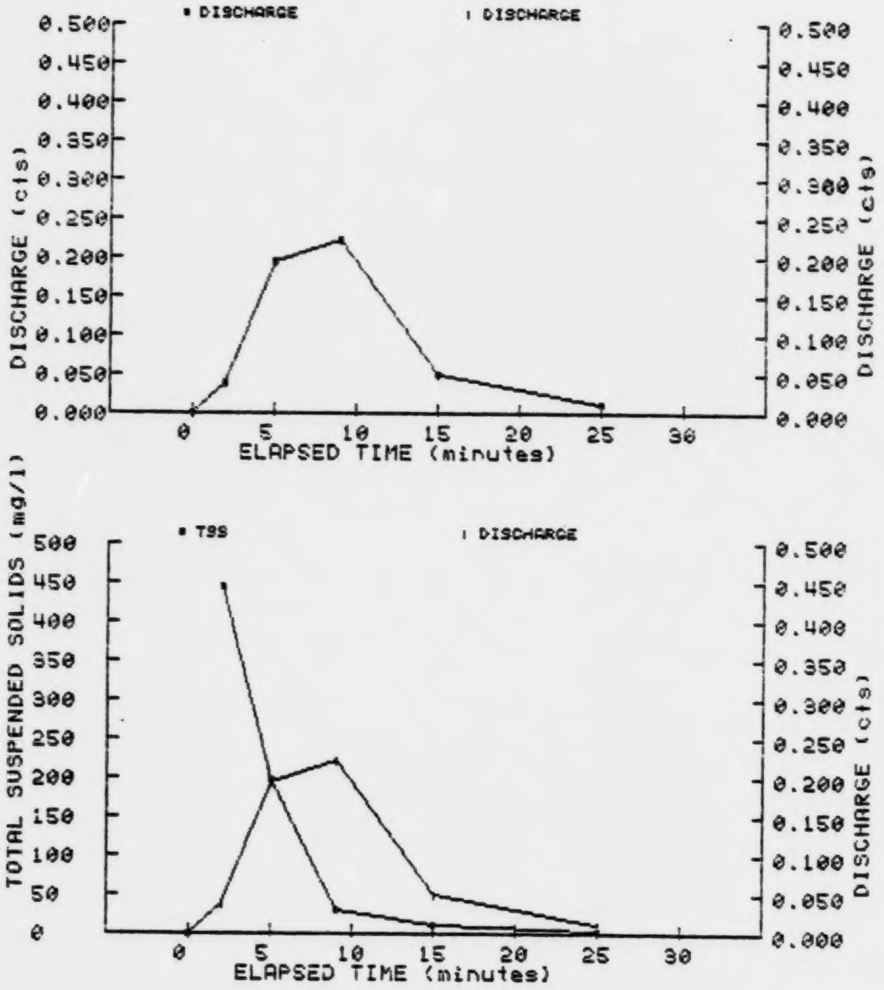


FIG.C-31. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 5/11/82

CONVENTIONAL ASPHALT LOT

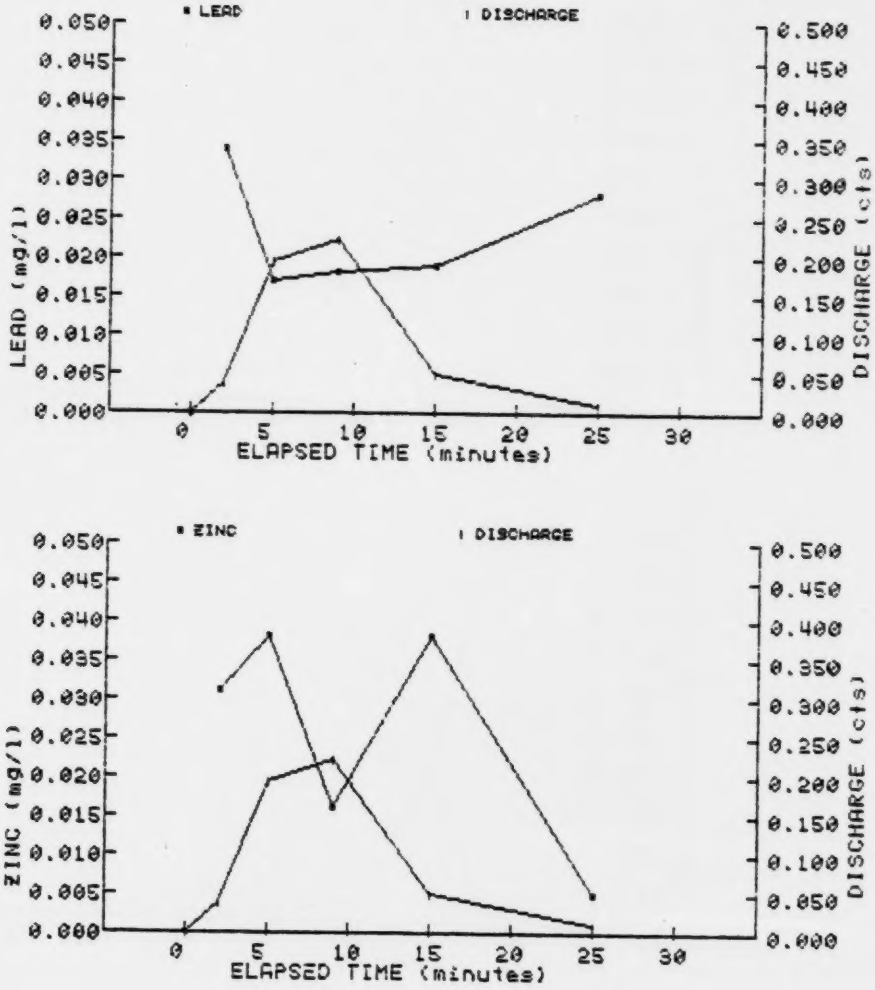


FIG. C-32. LEAD AND ZINC VALUES RECORDED 5/11/82.

CONVENTIONAL ASPHALT LOT

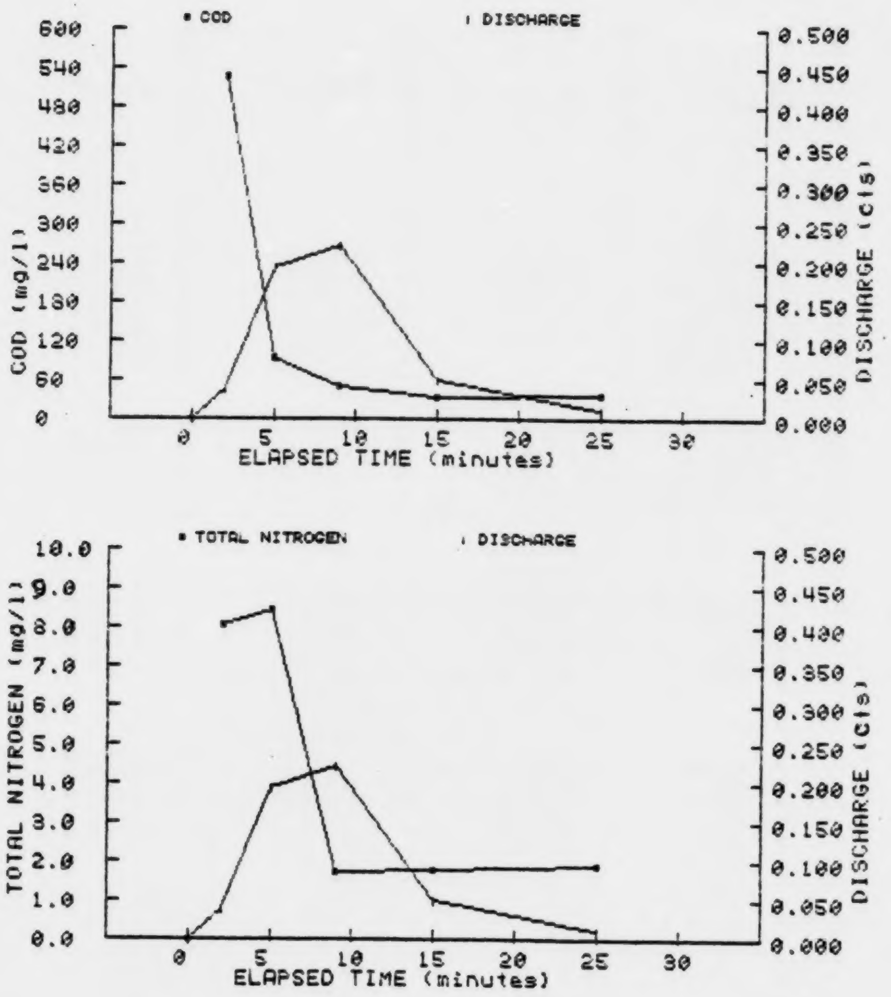


FIG. C-33. COD AND TOTAL NITROGEN VALUES RECORDED 5/11/82.

CONVENTIONAL ASPHALT LOT

TSS

```
EQUATION                      A           B       R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.13165     0.13722     0.37110       0.28828          25
Y = A(EXP(BX))             0.01240     0.01522     0.38743       1.67088          25
Y = A(X**B)                0.00788     0.75508     0.89714       0.18927          25
Y = A + BX                 0.04837     0.00281     0.87821       0.12686          25
```

COD

```
EQUATION                      A           B       R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          0.11564     0.08500     0.53755       0.12723          25
Y = A(EXP(BX))             0.02573     0.01073     0.24664       0.50789          25
Y = A(X**B)                0.01367     0.68198     0.93811       0.11347          25
Y = A + BX                 0.09754     0.00129     0.69637       0.10310          25
```

TKN

```
EQUATION                      A           B       R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))       1674.42773  1131.00830     0.07845    6256.10840          25
Y = A(EXP(BX))             0.02941     0.01538     0.07351    7099.29102          25
Y = A(X**B)                0.00972     1.07353     0.33719    7098.79492          25
Y = A + BX                 0.00793     0.00154     0.00849    6489.22363          25
```

Pb

```
EQUATION                      A           B       R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          3.92446     2.05754     0.09057      10.51553          25
Y = A(EXP(BX))             0.05039    -0.00816     0.02509      12.55818          25
Y = A(X**B)                0.00741     0.62821     0.13983      12.51971          25
Y = A + BX                 5.75725     0.00947     0.10023      11.02721          25
```

Zn

```
EQUATION                      A           B       R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))          2.63135     1.49620     0.12146       6.49401          25
Y = A(EXP(BX))             0.03256    -0.00839     0.02553       8.07194          25
Y = A(X**B)                0.00528     0.57352     0.11218       8.04644          25
Y = A + BX                 3.69469     0.00399     0.00486       6.91153          25
```

CONVENTIONAL CONCRETE LOT LOCATED AT LAVACA ST.-AUSTIN, TEXAS

```
           STORM DATE =    MAR,04,81
           STORM NO. =      1  NUMBER OF SAMPLES =       8
SA    Q     PB       CU       ZN       CD       TSS       VSS       TKN      P        OIL      COD       COL       BOD5    TIME
NO  CFS    MG/L     MG/L     MG/L     MG/L     MG/L      MG/L      MG/L     MG/L     MG/L     MG/L      NO/CC     MG/L    MIN
          10**-2   10**-2   10**-2   10**-2   10**-2    10**-2    10**-2   10**-2   10**-2   10**-2    10**-2    10**-2
 1 .00000   0.0      0.0      0.0      0.0       0.0       0.0       0.0      0.0      0.0      0.0       0.0      0.0     0.
 2 .12000   2.0      0.3      3.1      1.0    2660.0     840.0      69.0      4.0    125.0   2160.0    1500.0    110.0    45.
 3 .19000   2.0      0.5      4.0      1.0    1500.0     500.0      32.0      3.4    100.0   1590.0    1375.0    160.0    55.
 4 .20000   2.0      0.7      3.1      1.0    1150.0     340.0      60.0      3.2     14.0   1970.0    5750.0    220.0    60.
 5 .19000   2.0      0.6      3.2      1.0     460.0     200.0     143.0      7.1      4.0   1400.0   12188.0    290.0    70.
 6 .15000   2.0      0.4      3.0      1.0     710.0     220.0      44.0      4.2      4.0   1970.0   13750.0    138.0    80.
 7 .12000   2.0      0.7      3.7      1.0     710.0     270.0      54.0      2.9      3.0   2360.0   12375.0    170.0    90.
 8 .07000   2.0      0.7      3.4      1.0     580.0     180.0      43.0      3.2      3.0   1200.0   15812.0    170.0   110.

     TOTAL FLOW AND POLLUTANTS.
     ********************************
                                                                     SP       SOIL      SCOD      SCOL     SBOD5
   VO      SPB      SCU      SZN      SCD      STSS      SVSS      STKN      LB       LB        LB        NO        LB
  CU.FT    LB       LB       LB       LB       LB        LB        LB      10**-5   10**-5              10**8
  10**1  10**-5   10**-5   10**-5   10**-5
   0.00   0.000    0.000    0.000    0.000   0.0000    0.0000    0.0000    0.000     0.000    0.0000    0.000    0.0000
  16.20  20.250    3.037   31.387   10.125   0.2693    0.0850    0.0070   40.500  1265.625    0.2187    0.688    0.0111
  25.50  31.875    5.944   54.637   15.937   0.3565    0.1141    0.0088   60.262  1846.875    0.3111    1.051    0.0204
  31.35  39.187    8.503   65.972   19.594   0.3986    0.1265    0.0110   71.962  1898.062    0.3831    2.004    0.0285
  43.05  53.812   12.891   89.372   26.906   0.4322    0.1412    0.0215  123.881  1927.312    0.4855    6.044    0.0497
  53.25  66.562   15.441  108.497   33.281   0.4775    0.1552    0.0243  150.656  1952.811    0.6111   10.018    0.0585
  61.35  76.687   18.984  127.228   38.344   0.5134    0.1689    0.0270  165.337  1967.999    0.7306   12.858    0.0671
  72.75  90.937   23.972  151.453   45.469   0.5547    0.1817    0.0301  188.137  1989.373    0.8161   17.965    0.0792

     RUNOFF AND POLLUTANT PER UNIT AREA.
     ******************************************
                                                                      P        OIL       COD       COL      BOD5
   VO      PB       CU       ZN       CD       TSS       VSS       TKN      LB/AC    LB/AC     LB/AC     NO/AC    LB/AC
   IN     LB/AC    LB/AC    LB/AC    LB/AC    LB/AC     LB/AC     LB/AC    10**-5   10**-5              10**8
         10**-5   10**-5   10**-5   10**-5
   0.54  246.443   64.964  410.442  123.221   1.5033    0.4924    0.0816  509.857  5391.256    2.2116   48.686    0.2146

     AVERAGE POLLUTANTS IN THE SAMPLE.
     *********************************

   PB       CU       ZN       CD       TSS       VSS       TKN      P        OIL      COD       COL      BOD5
  MG/L     MG/L     MG/L     MG/L     MG/L      MG/L      MG/L     MG/L     MG/L     MG/L      NO/CC    MG/L
 10**-2   10**-2   10**-2   10**-2   10**-2    10**-2    10**-2   10**-2   10**-2   10**-2    10**2    10**-2
    2.0      0.5      3.3      1.0   1221.4     400.1      66.3      4.1     43.8   1796.9      0.9     174.4
```

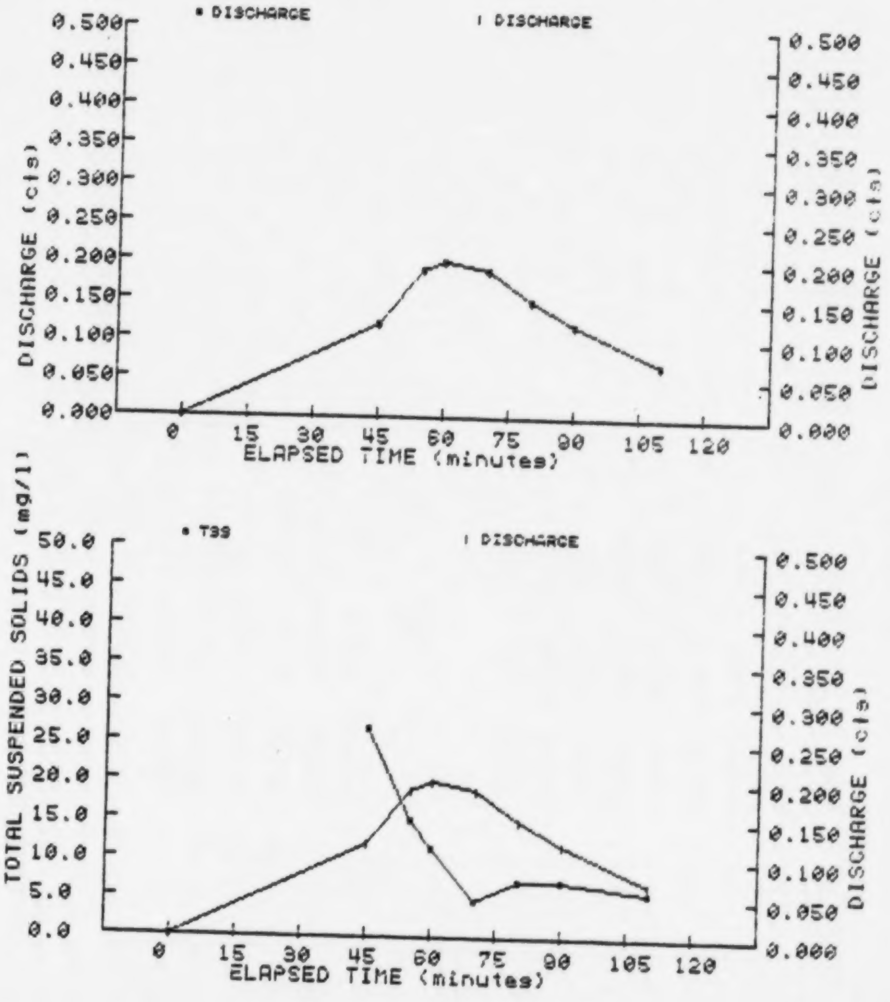


FIG.C-34. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 3/4/81.
CONVENTIONAL CONCRETE LOT

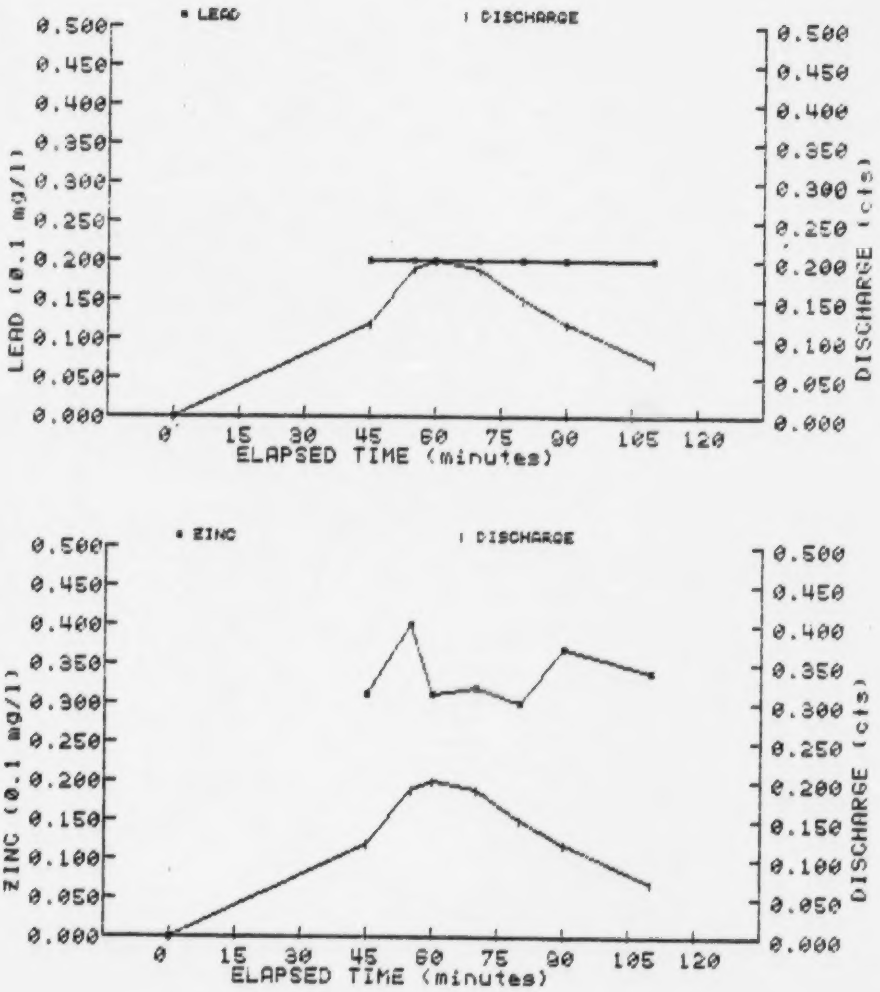


FIG. C-35. LEAD AND ZINC VALUES RECORDED 3/4/81.

CONVENTIONAL CONCRETE LOT

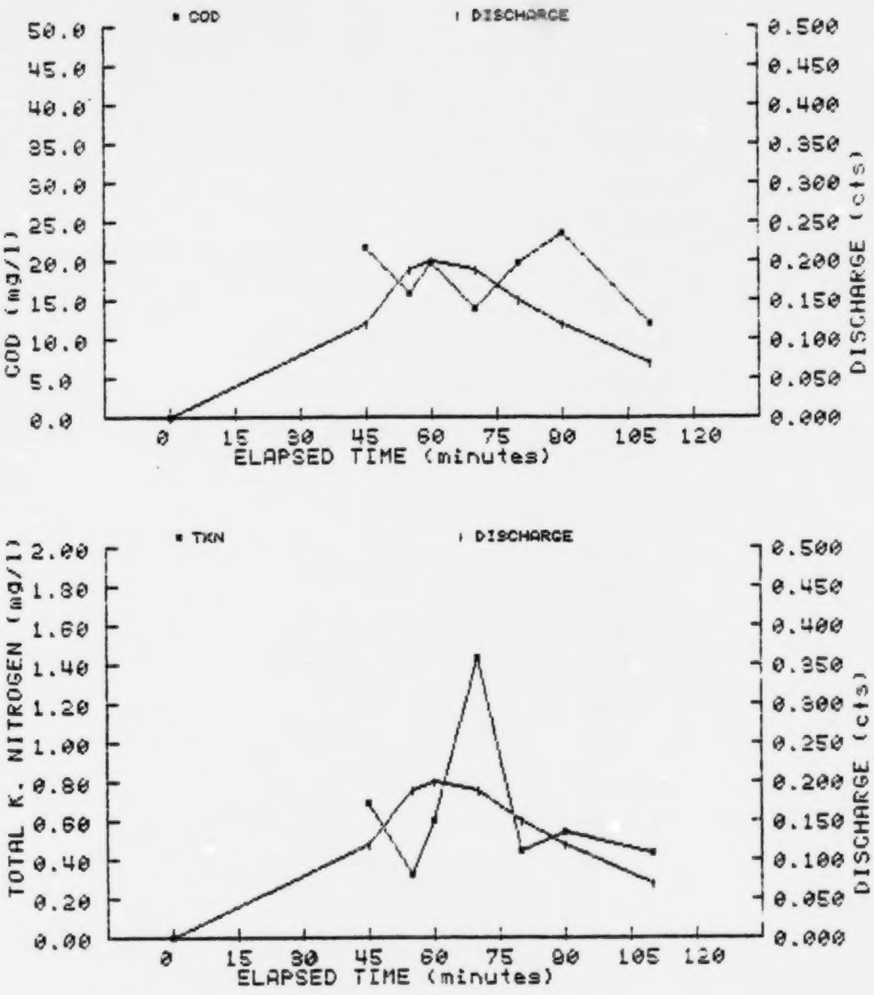


FIG.C-36. COD AND TKN VALUES RECORDED 3/4/81.

CONVENTIONAL CONCRETE LOT

CONVENTIONAL CONCRETE LOT LOCATED AT LAVACA STREET-AUSTIN, TEXAS

```
          STORM DATE =   JUN,03,81
          STORM NO. =        2  NUMBER OF SAMPLES =      11
SA    Q      PB       CU       ZN       CD       TSS      VSS      TKN       P       OIL      COD      COL     BOD5     TIME
NO   CFS    MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     NO/CC    MG/L     MIN
          10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**2   10**-2
1 .00000    0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.

2 .02000    0.5      3.0      0.8      0.2   5030.0   1270.0    136.0      4.6      4.0   2720.0    14000    360.0     10.

3 .09000    9.0      3.0      0.8      0.1   2120.0    440.0     31.0      1.5      3.0   2320.0    14000    200.0     20.

4 .10000    4.5      3.0      0.8      0.1   1320.0    420.0     46.0      6.0      2.0    930.0    15000    200.0     30.

5 .10000    4.2      3.0      0.8      0.1    880.0    220.0     31.0      0.6    250.0   1130.0    14000    290.0     40.

6 .08000    3.0      3.0      0.8      0.0   5700.0    100.0     36.0      3.6    216.0   1720.0    19000    260.0     50.

7 .04000    1.8      3.0      0.8      0.0    520.0    180.0      3.0      2.0    121.0   1920.0    22000    260.0     60.

8 .05000    0.7      3.0      0.8      0.2    790.0    300.0     45.0      1.3     58.0   1720.0    31000    180.0     70.

9 .04000    0.8      3.0      0.8      0.1    570.0    200.0      1.0      2.5     48.0   1920.0    16000    210.0     80.

0 .03000    1.3      3.0      0.8      0.0    390.0    130.0     17.0      2.7     56.0   1520.0    21000    210.0     90.

1 .02500    2.7      3.0      0.8      0.0    320.0    120.0     17.0      3.7      1.0   1520.0    22000    260.0    100.

          TOTAL FLOW AND POLLUTANTS.
          **********************************
  VO      SPB      SCU      SZN      SCD      STSS     SVSS     STKN      SP      SOIL      SCOD     SCOL    SBOD5
 CU.FT    LB       LB       LB       LB        LB       LB       LB       LB       LB        LB       NO       LB
 10**1                                                                                           10**10
  0.00  0.0000  0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000  0.0000

  0.40  0.0000  0.0000   0.0000   0.0000   0.0189   0.0048   0.0005   0.0000   0.0000   0.0102   0.0024  0.0013

  3.90  0.0002  0.0001   0.0000   0.0000   0.0626   0.0138   0.0011   0.0000   0.0001   0.0580   0.0155  0.0055

  9.40  0.0003  0.0002   0.0000   0.0000   0.1094   0.0288   0.0028   0.0003   0.0001   0.0912   0.0397  0.0126

 15.40  0.0005  0.0003   0.0001   0.0000   0.1426   0.0370   0.0040   0.0003   0.0095   0.1336   0.0635  0.0235

 21.00  0.0006  0.0004   0.0001   0.0000   0.3350   0.0404   0.0052   0.0004   0.0168   0.1916   0.0926  0.0322

 25.20  0.0007  0.0005   0.0001   0.0000   0.3486   0.0451   0.0052   0.0005   0.0200   0.2420   0.1187  0.0391

 28.50  0.0007  0.0005   0.0001   0.0000   0.3649   0.0513   0.0062   0.0005   0.0212   0.2775   0.1477  0.0428

 31.20  0.0007  0.0006   0.0002   0.0000   0.3745   0.0547   0.0062   0.0005   0.0220   0.3099   0.1600  0.0463

 33.30  0.0007  0.0006   0.0002   0.0000   0.3797   0.0564   0.0064   0.0006   0.0227   0.3298   0.1725  0.0491

 34.95  0.0007  0.0007   0.0002   0.0000   0.3830   0.0577   0.0066   0.0006   0.0227   0.3455   0.1827  0.0518
          RUNOFF AND POLLUTANT PER UNIT AREA.
          ****************************************
  VO      PB       CU       ZN       CD       TSS      VSS      TKN       P       OIL       COD      COL     BOD5

  IN    LB/AC    LB/AC    LB/AC    LB/AC    LB/AC    LB/AC    LB/AC    LB/AC    LB/AC    LB/AC    NO/AC   LB/A
                                                                                                  10**10
  0.26  0.0020  0.0018   0.0005   0.0001   1.0379   0.1562   0.0179   0.0017   0.0616   0.9363   0.4953  0.1403
          AVERAGE POLLUTANTS IN THE SAMPLE.
          *********************************
  PB       CU       ZN       CD       TSS      VSS      TKN       P       OIL      COD      COL     BOD5
 MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     MG/L     NO/CC    MG/L
10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**-2   10**2   10**-2
   3.3      3.0      0.8      0.1   1755.2    264.3     10.2      2.8    104.2   1583.5      1.8    237.3
```

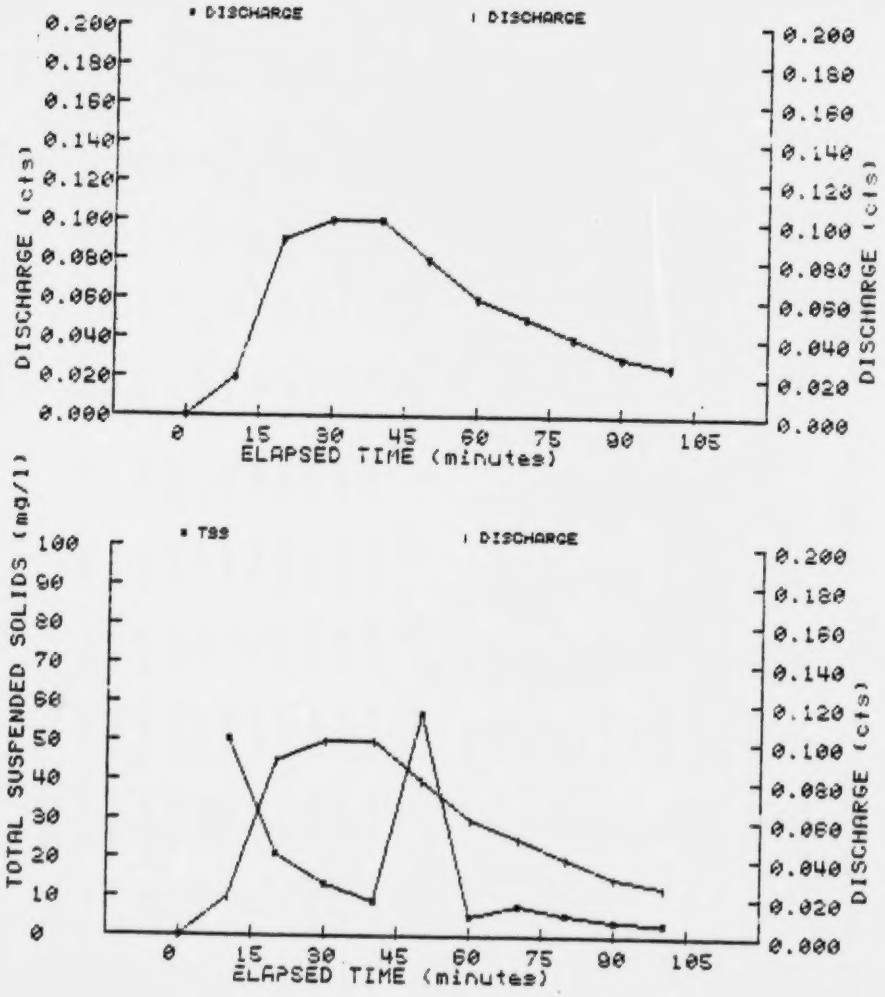


FIG.C-37. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 6/3/81.

CONVENTIONAL CONCRETE LOT

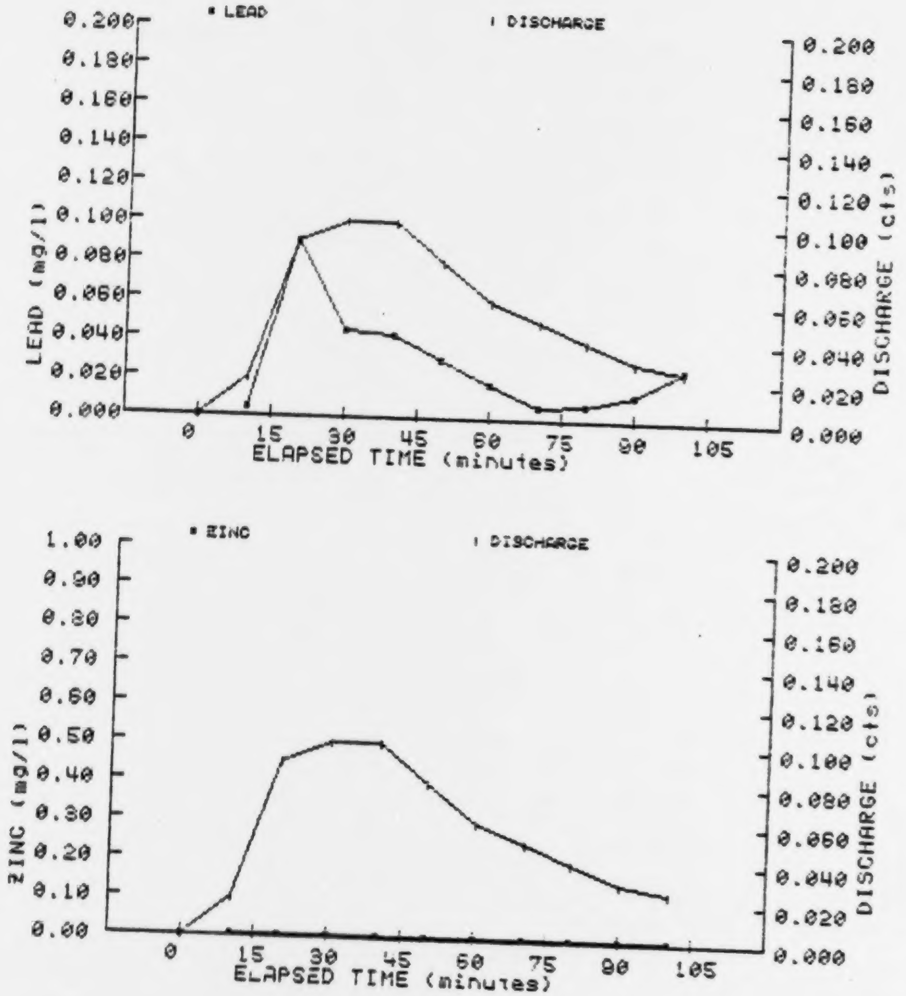


FIG.C-38. LEAD AND ZINC VALUES RECORDED 6/3/81.

CONVENTIONAL CONCRETE LOT

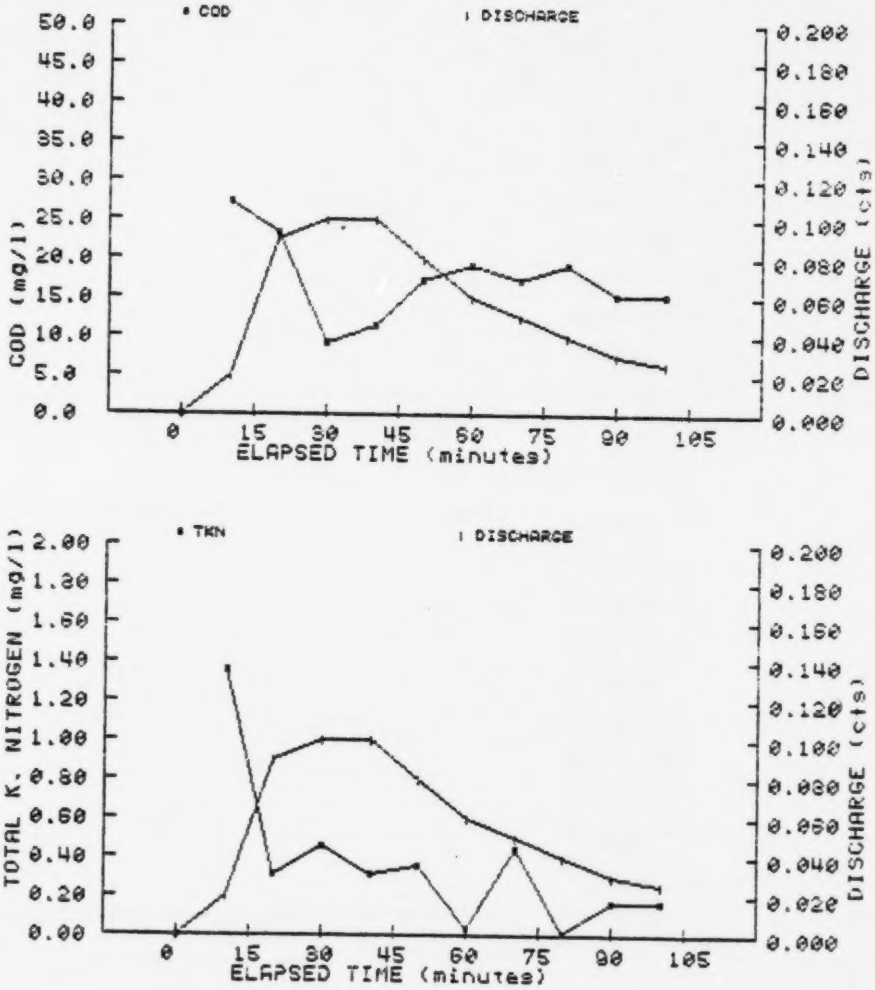


FIG. C-39 COD AND TKN VALUES RECORDED 6/3/81.
CONVENTIONAL CONCRETE LOT

CONVENTIONAL CONCRETE LOT AT LAVACA STREET-AUSTIN, TEXAS

```
        STORM DATE =   OCT,07,81
        STORM NO. =        3  NUMBER OF SAMPLES =       11
SA    Q     PB       CU        ZN        CD        TSS       VSS       TKN       P         OIL       COD       COL        BOD5      TIME
NO   CFS    MG/L     MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      NO/CC      MG/L      MIN
            10**-2   10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2     10**-2
1 .00000    0.0      0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0        0.0       0.
2 .04000    2.2      0.6       1.2       0.0   10900.0    3000.0     102.0       4.8      36.0    5790.0   82300.0      540.0      10.
3 .05000    0.3      0.3       1.2       0.0    1400.0     560.0       5.0       4.0      25.0    4800.0   22500.0      800.0      20.
4 .07000    1.1      0.3       1.5       0.0     640.0     320.0       5.0       4.5      20.0    2620.0   23400.0      960.0      30.
5 .06000    0.4      0.2       1.1       0.0     780.0     500.0       5.0       2.9      10.0    1430.0   22500.0      770.0      40.
6 .05000    0.9      0.3       0.8       0.0     390.0     230.0       5.0       4.5     120.0    4000.0    7800.0      610.0      50.
7 .04000    0.9      0.3       0.8       0.0     300.0     200.0       5.0       3.7     151.0    2220.0   22500.0      500.0      60.
8 .03000    1.1      0.3       0.9       0.0     170.0     120.0       5.0       2.9       9.0    3010.0     900.0      410.0      70.
9 .02000    0.2      0.2       0.7       0.0     800.0     390.0      78.0       4.5     143.0    3410.0   23400.0      410.0      80.
0 .01000    0.4      0.3       0.9       0.0     230.0     140.0     134.0       3.2       9.0    1230.0   19900.0      510.0      90.
1 .01000    0.4      0.2       0.6       0.0     280.0     190.0     171.0       2.7      10.0    1030.0   19900.0      410.0     100.

        TOTAL FLOW AND POLLUTANTS.
        **********************************

  VO      SPB      SCU       SZN       SCD       STSS      SVSS      STKN      SP        SOIL      SCOD      SCOL      SBOD5
 CU.FT    LB       LB        LB        LB        LB        LB        LB        LB        LB        LB        NO        LB
 10**1   10**-5   10**-5    10**-5    10**-5                                   10**-5    10**-5              10**8
 0.00    0.000    0.000     0.000     0.000     0.0000    0.0000    0.0000     0.000     0.000    0.0000     0.000    0.0000
 1.20    1.650    0.450     0.900     0.037     0.0817    0.0225    0.0008     3.600    27.000    0.0434     2.798    0.0040
 3.90    2.154    0.956     2.925     0.054     0.1054    0.0319    0.0008    10.350    69.187    0.1244     4.519    0.0175
 7.50    4.631    1.631     6.300     0.077     0.1198    0.0391    0.0010    20.475   114.187    0.1834     6.906    0.0391
11.40    5.406    2.119     8.981     0.101     0.1388    0.0513    0.0011    27.544   138.562    0.2231     9.392    0.0579
14.70    7.462    2.737    10.631     0.122     0.1468    0.0561    0.0012    36.825   386.062    0.3056    10.122    0.0705
17.40    8.981    3.244    11.981     0.139     0.1519    0.0595    0.0013    43.069   640.875    0.3431    11.843    0.0789
19.50   10.425    3.637    13.162     0.152     0.1541    0.0610    0.0013    46.875   652.687    0.3826    11.897    0.0843
21.00   10.612    3.825    13.819     0.161     0.1616    0.0647    0.0021    51.094   786.750    0.4145    12.891    0.0882
21.90   10.837    3.994    14.325     0.167     0.1629    0.0655    0.0028    52.894   791.812    0.4215    13.399    0.0910
22.50   10.987    4.069    14.550     0.171     0.1640    0.0662    0.0035    53.906   795.562    0.4253    13.737    0.0926

        RUNOFF AND POLLUTANT PER UNIT AREA.
        ****************************************

  VO      PB       CU        ZN        CD        TSS       VSS       TKN       P         OIL       COD       COL       BOD5
  IN     LB/AC    LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     LB/AC     NO/AC     LB/AC
         10**-5   10**-5    10**-5    10**-5                                   10**-5    10**-5              10**8
 0.17   29.776   11.026    39.431     0.462     0.4444    0.1794    0.0094   146.087  2155.994    1.1526    17.227    0.2509

        AVERAGE POLLUTANTS IN THE SAMPLE.
        *********************************

  PB       CU        ZN        CD        TSS       VSS       TKN       P         OIL       COD       COL       BOD5
 MG/L     MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      MG/L      NO/CC     MG/L
10**-2   10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**-2    10**2     10**-2
  0.8      0.3       1.0       0.0    1167.4     471.2      24.7       3.8      56.6    3028.0       2.2     659.0
```

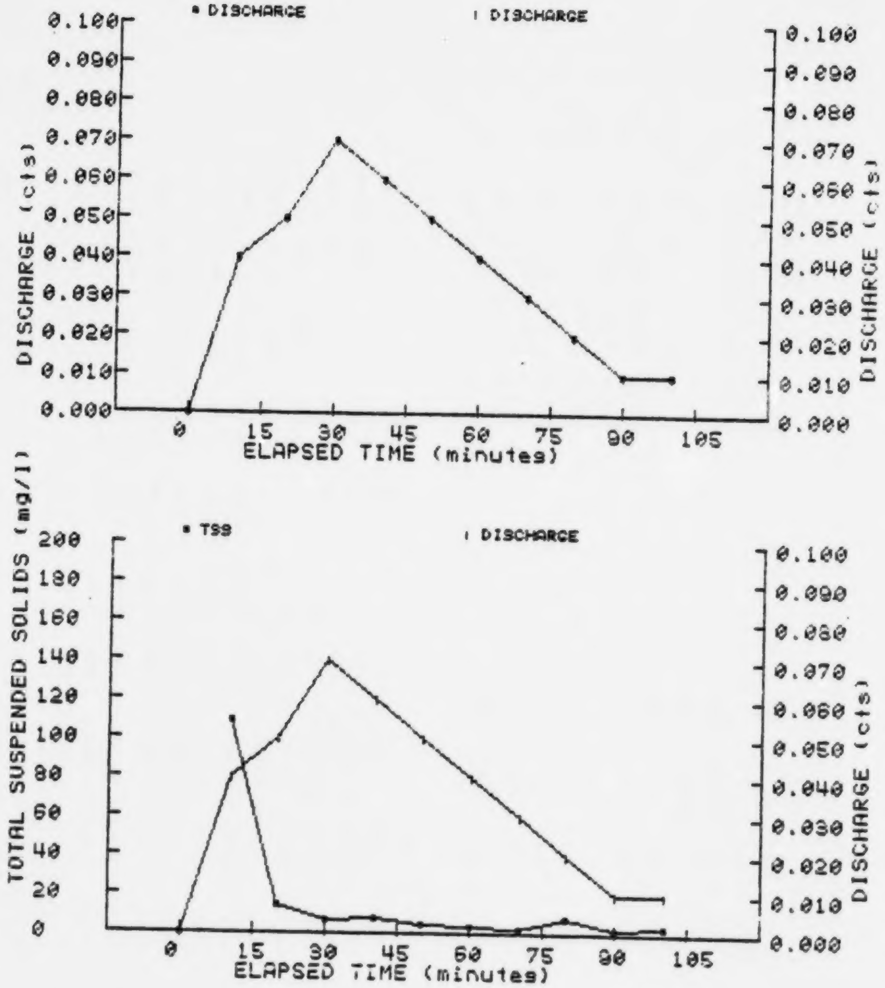


FIG. C-40. DISCHARGE AND TOTAL SUSPENDED SOLIDS RECORDED 10/7/81

CONVENTIONAL CONCRETE LOT

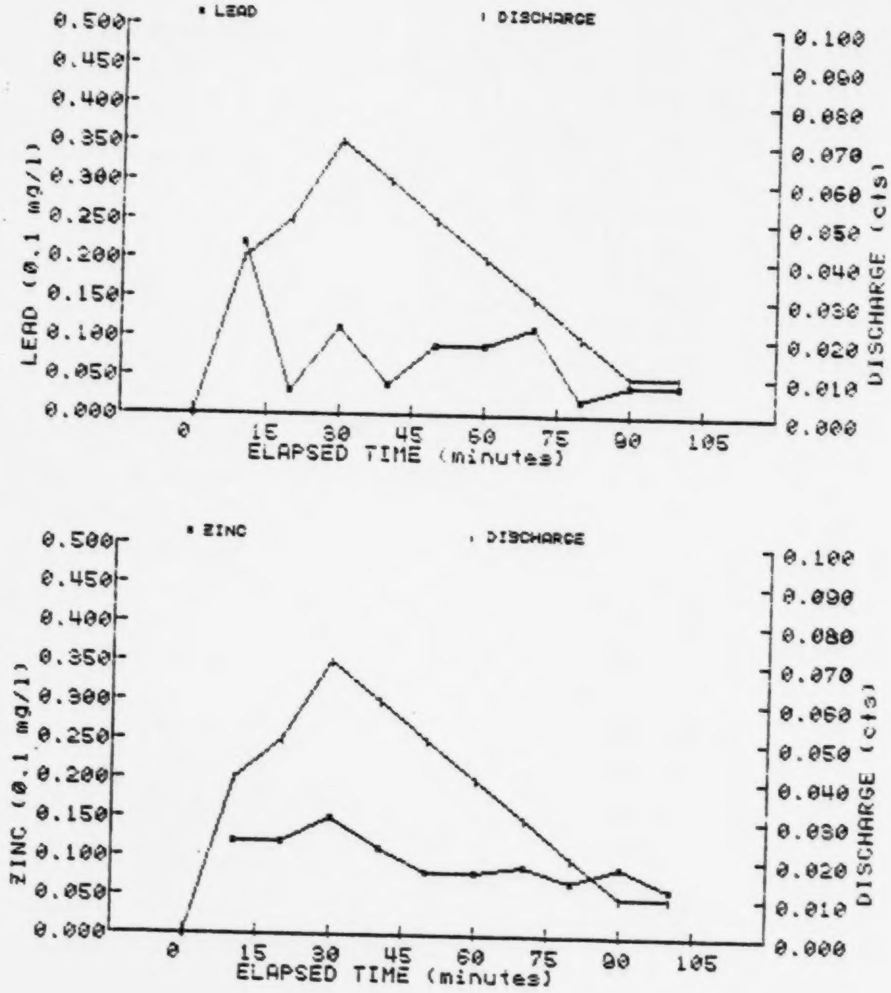


FIG. C-41. LEAD AND ZINC VALUES RECORDED 10/7/81.

CONVENTIONAL CONCRETE LOT

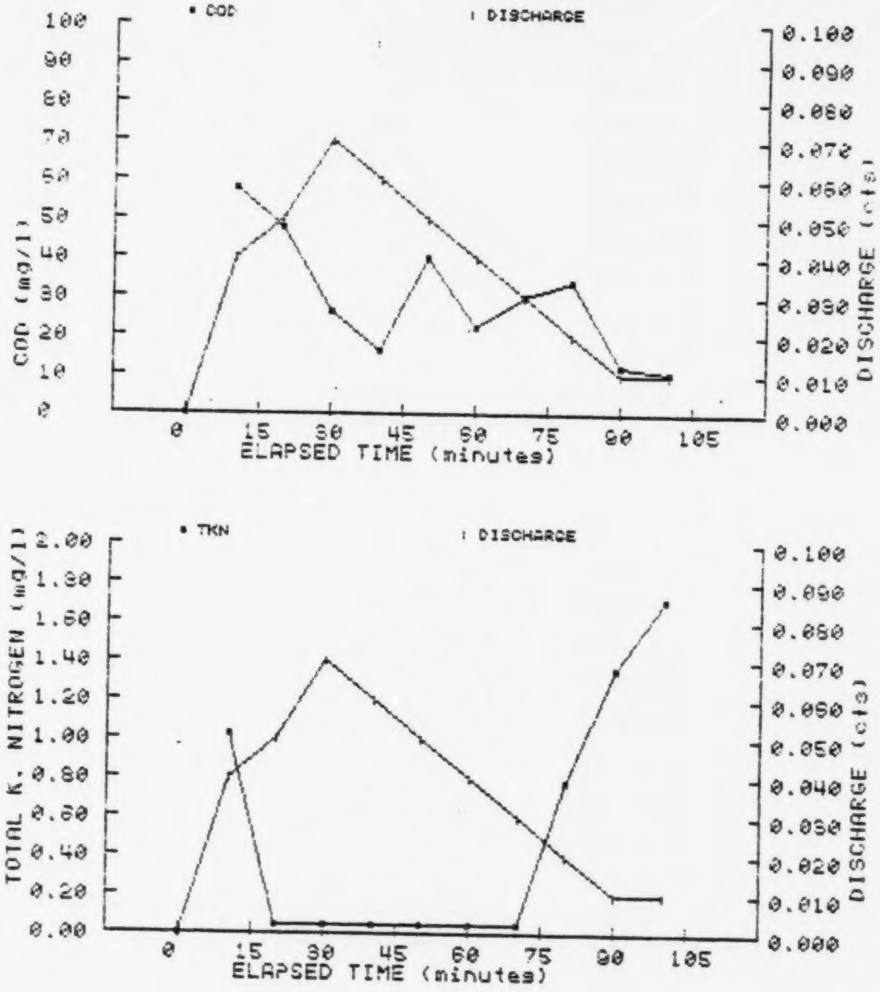


FIG. C-42. COD AND TKN VALUES RECORDED 10/7/81.

CONVENTIONAL CONCRETE LOT

TSS

```
EQUATION                    A          B          R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))        0.15721    0.06817    0.38237      0.12836            28
Y = A(EXP(BX))           0.03072    0.00663    0.32216      0.70638            28
Y = A(X**B)              0.00963    0.61885    0.98784      0.04828            28
Y = A + BX               0.08129    0.00083    0.85519      0.06216            28
```

COD

```
EQUATION                    A          B          R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))        0.13330    0.06954    0.24835      0.17924            28
Y = A(EXP(BX))           0.02036    0.00758    0.40803      0.88291            28
Y = A(X**B)              0.00793    0.62448    0.97460      0.10590            28
Y = A + BX              -0.01517    0.00112    0.97876      0.03013            28
```

TKN

```
EQUATION                    A          B          R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))        0.03788    0.02187    0.16166      0.07380            28
Y = A(EXP(BX))           0.00652    0.00727    0.47032      0.20455            28
Y = A(X**B)              0.00333    0.54894    0.94291      0.06043            28
Y = A + BX              -0.02275    0.00041    0.84826      0.03140            28
```

Pb

```
EQUATION                    A          B          R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))       16.03762    7.83572    0.12629     30.53573            28
Y = A(EXP(BX))           0.09647    0.01562    0.20975     99.00584            28
Y = A(X**B)              0.00844    0.80877    0.19774     45.67223            28
Y = A + BX               1.57802    0.11781    0.43050     24.65310            28
```

Zn

```
EQUATION                    A          B          R-SQUARE   STANDARD ERROR   SAMPLE SIZE

Y = A + B(LOG(X))        9.79851    8.17666    0.07718     41.89037            28
Y = A(EXP(BX))           0.00121    0.01819    0.24625    107.39723            28
Y = A(X**B)              0.00367    0.76844    0.15458     51.15789            28
Y = A + BX             -22.98646    0.19202    0.64194     26.09364            28
```

APPENDIX D. WATER LEVEL IN THE BASE LAYER DURING FILLING

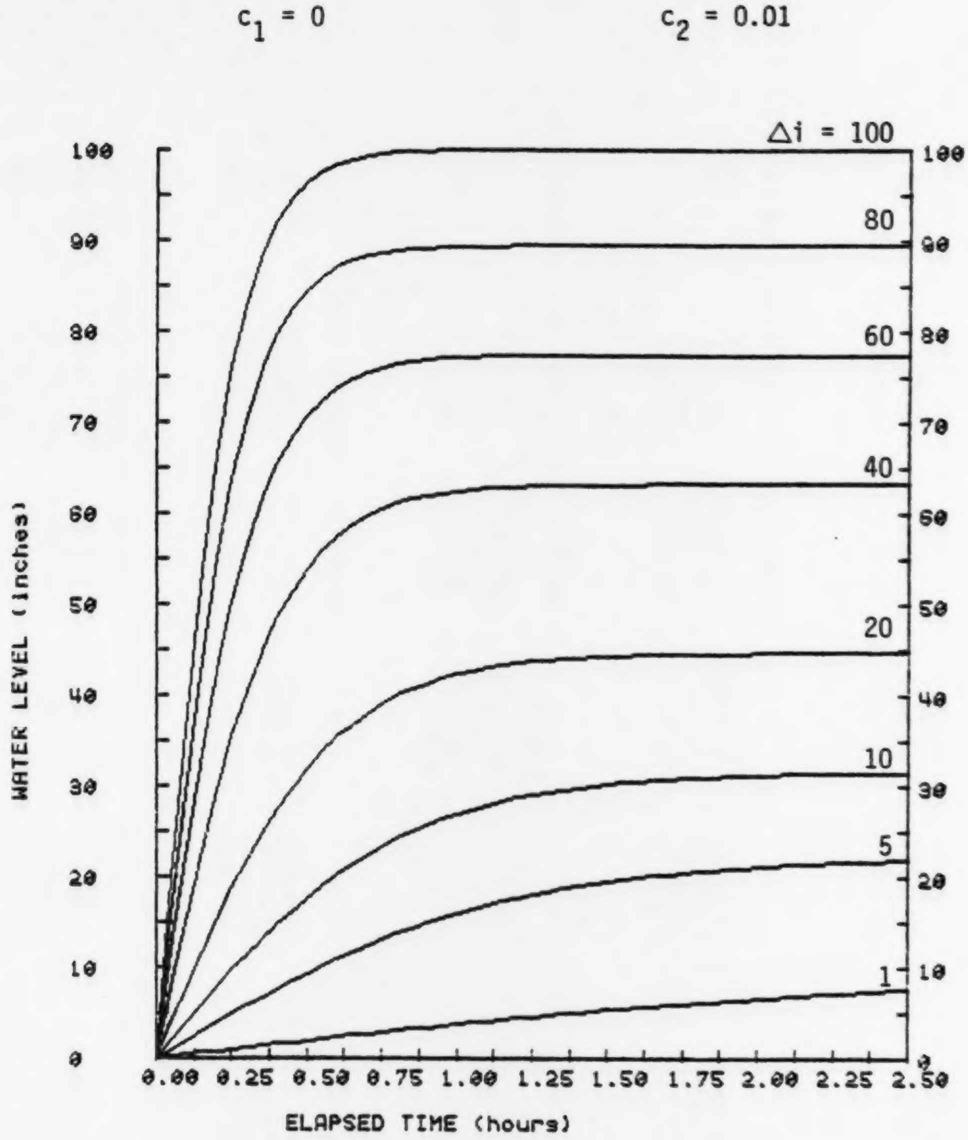


Fig. D1. Water level in the base layer during filling.

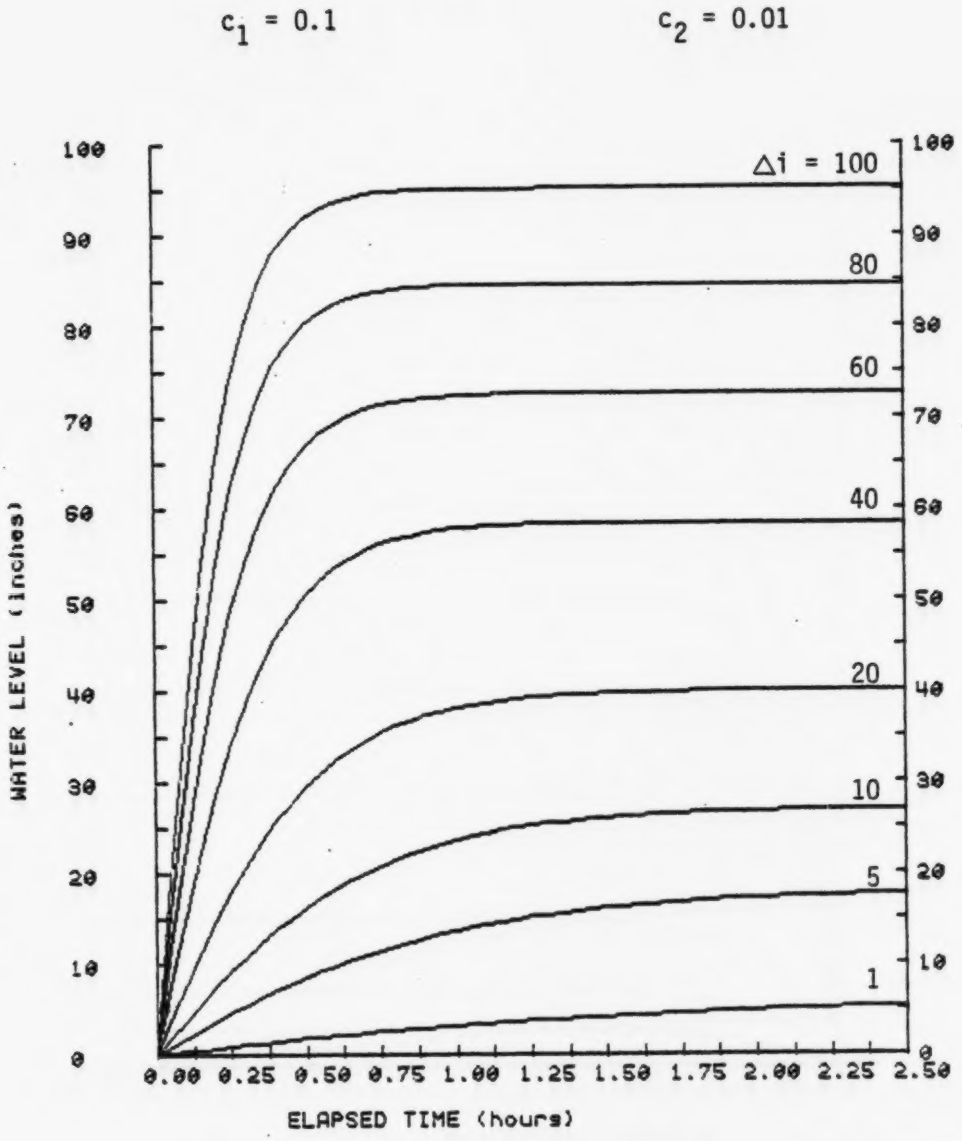


Fig. D2. Water level in the base layer during filling.

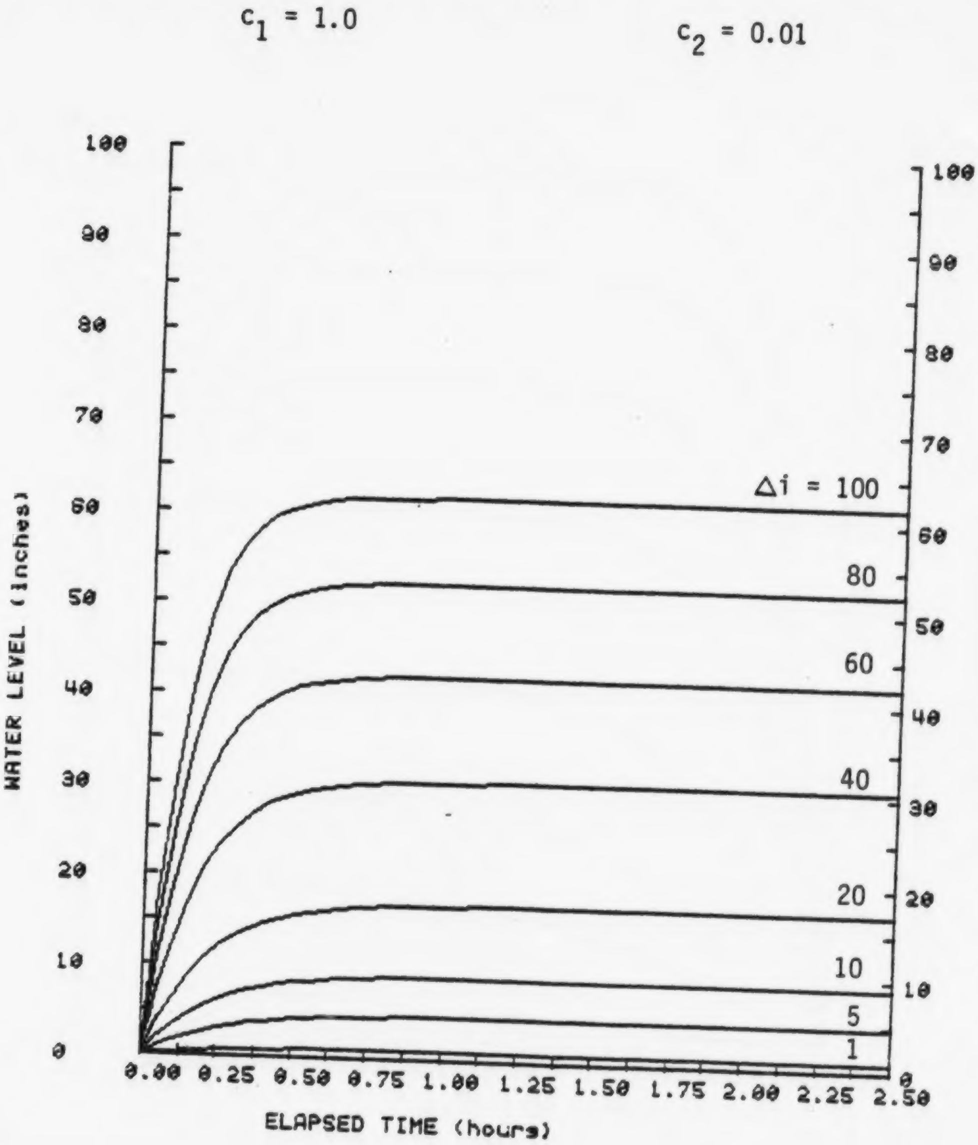


Fig. D3. Water level in the base layer during filling.

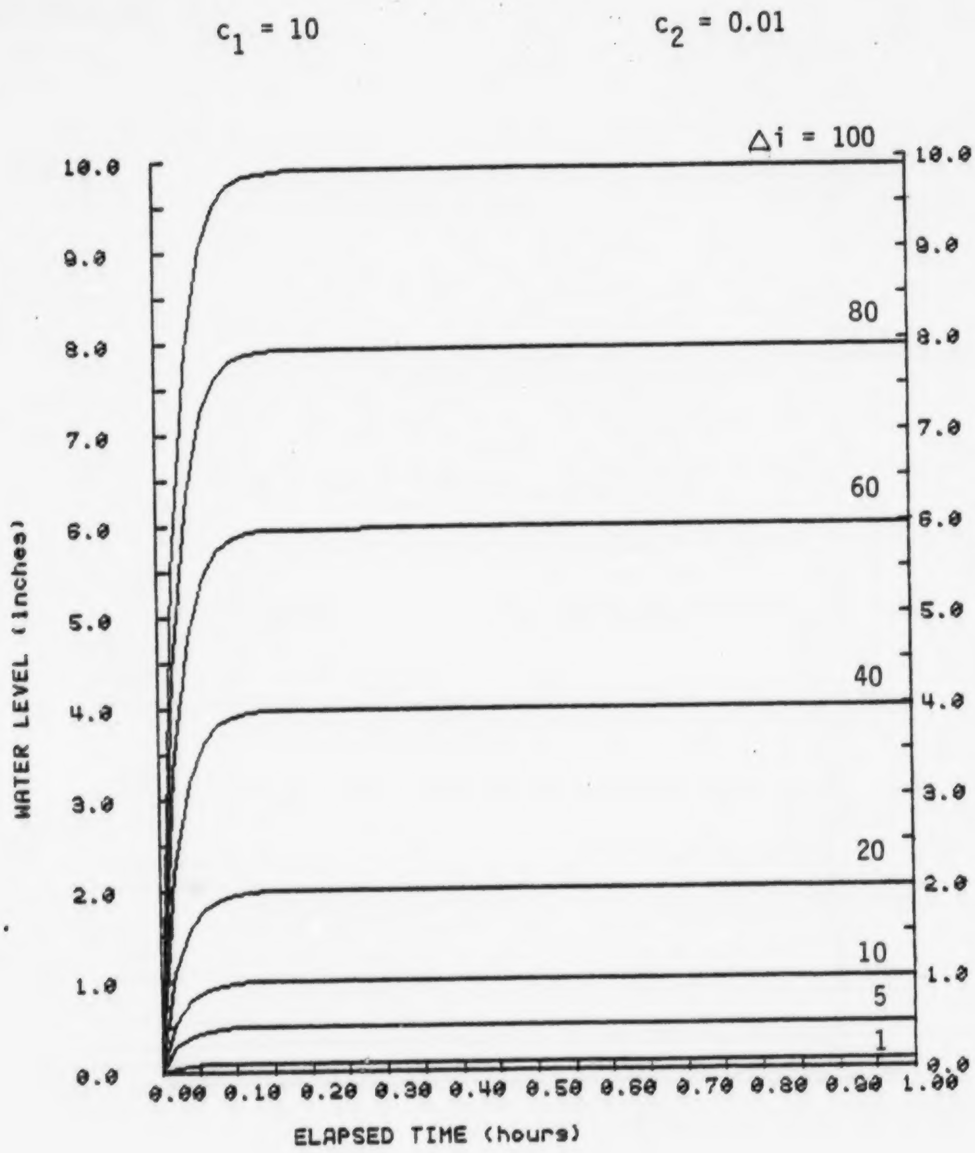


Fig. D4. Water level in the base layer during filling.

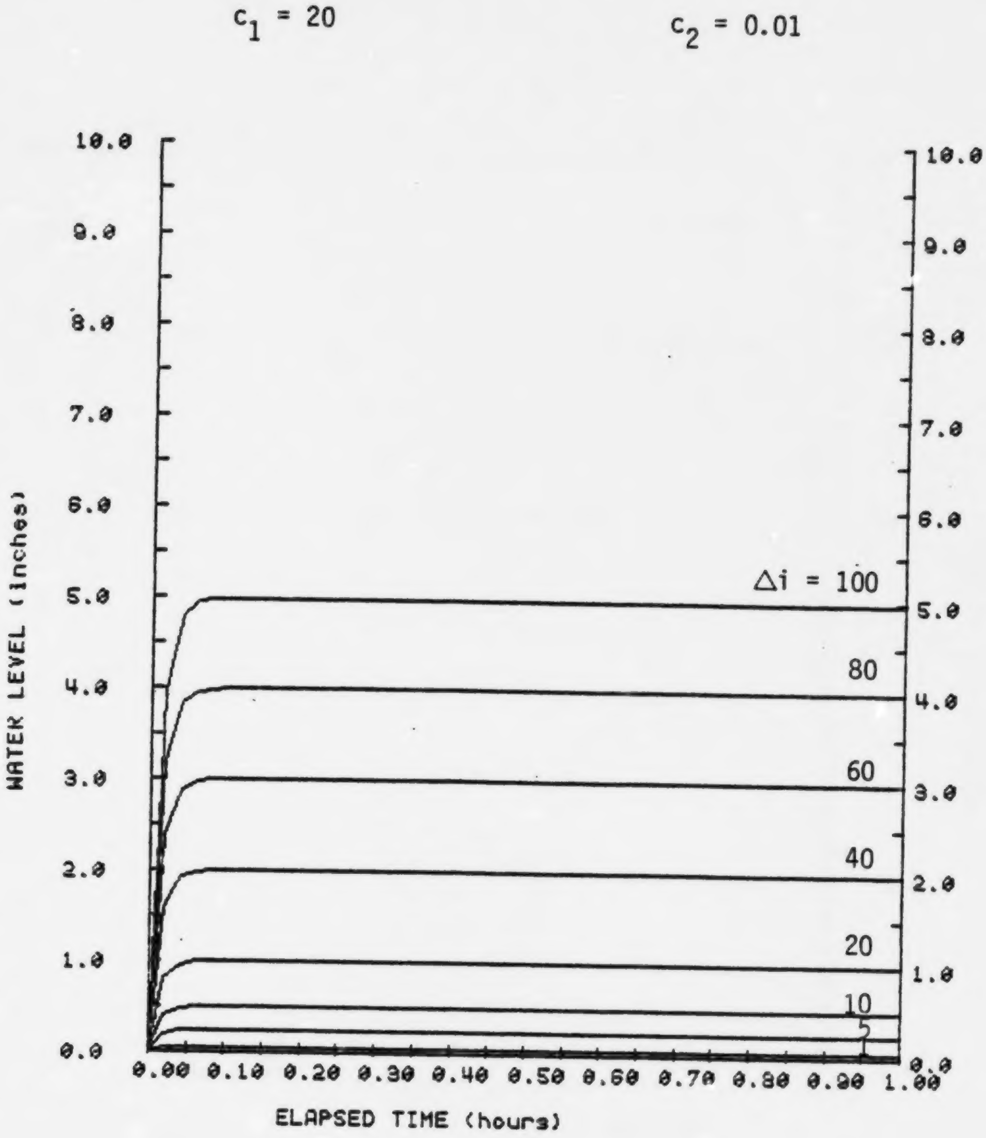


Fig. D5. Water level in the base layer during filling.

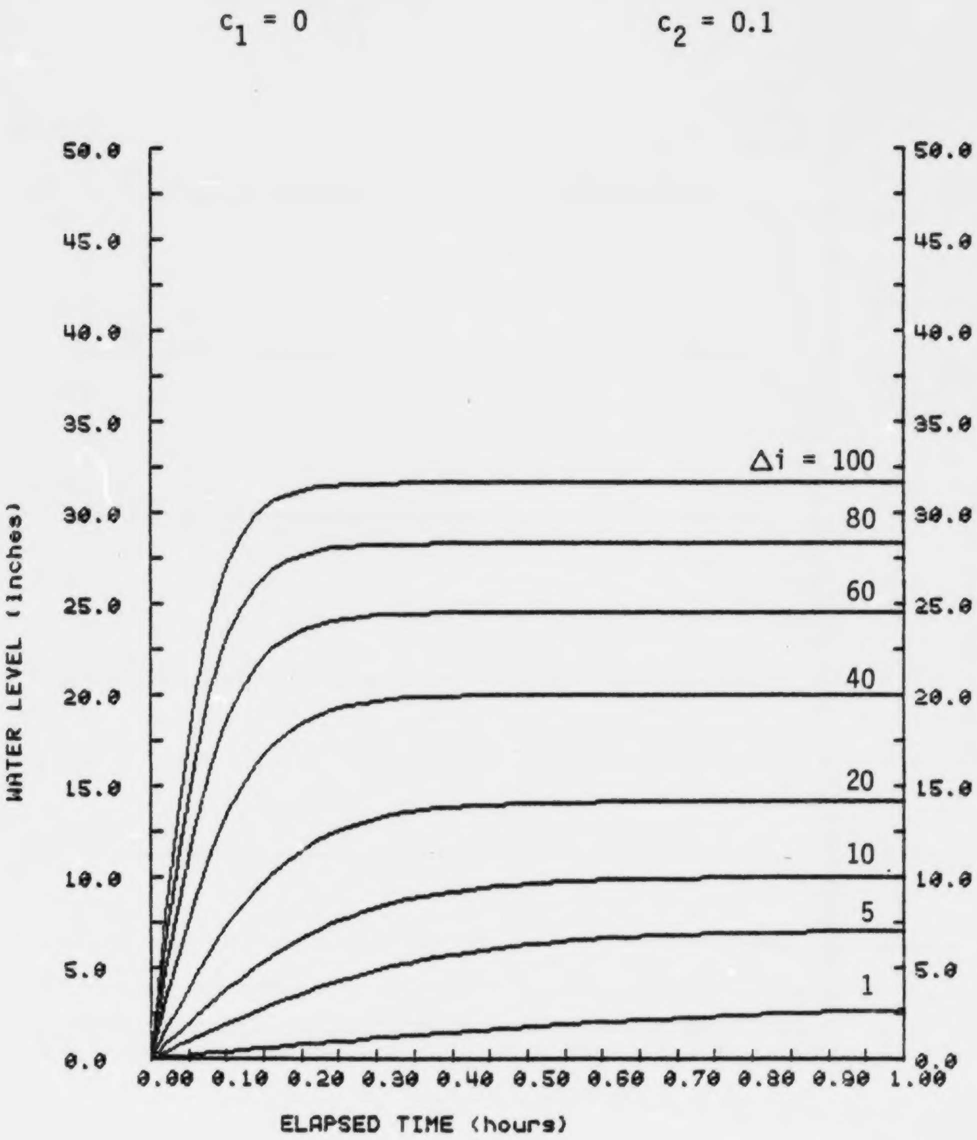


Fig. D6. Water level in the base layer during filling.

$c_1 = 10$ $c_2 = 0.1$

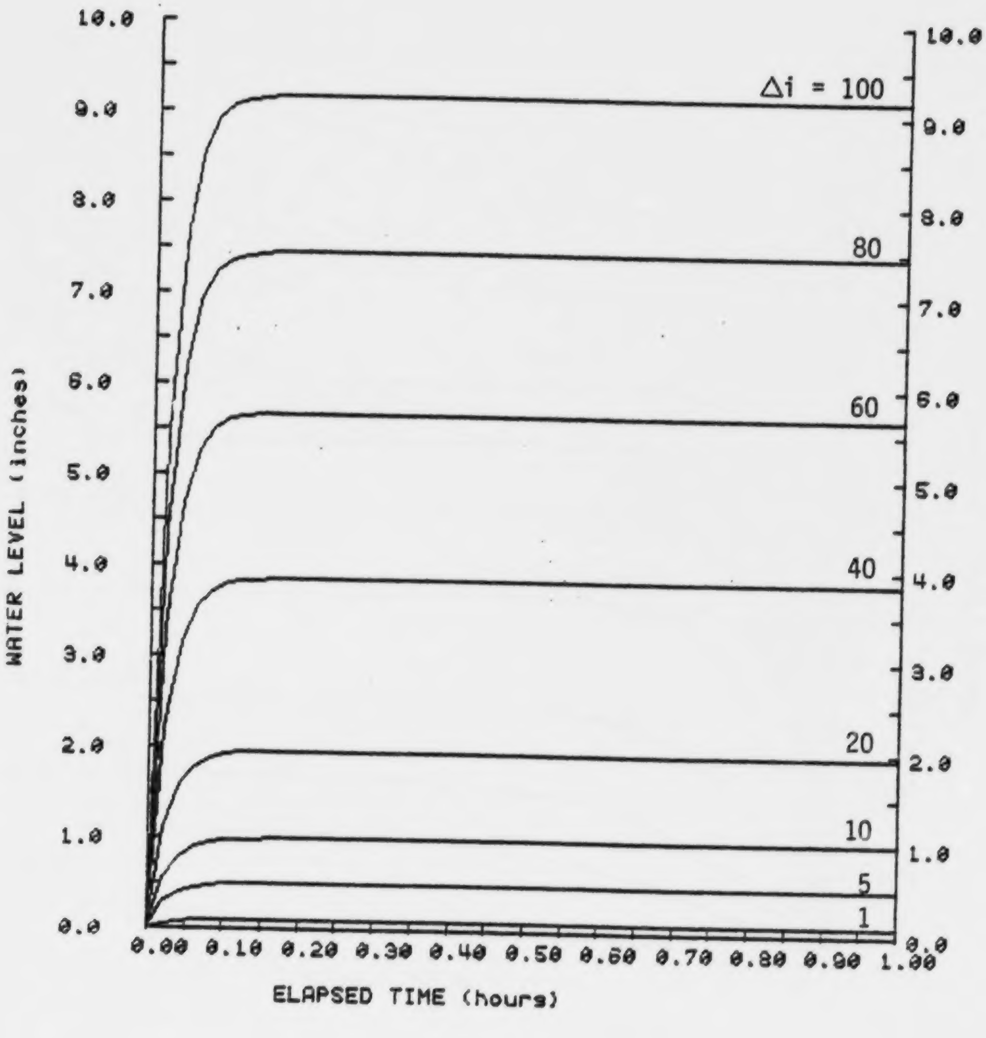


Fig. D7. Water level in the base layer during filling.

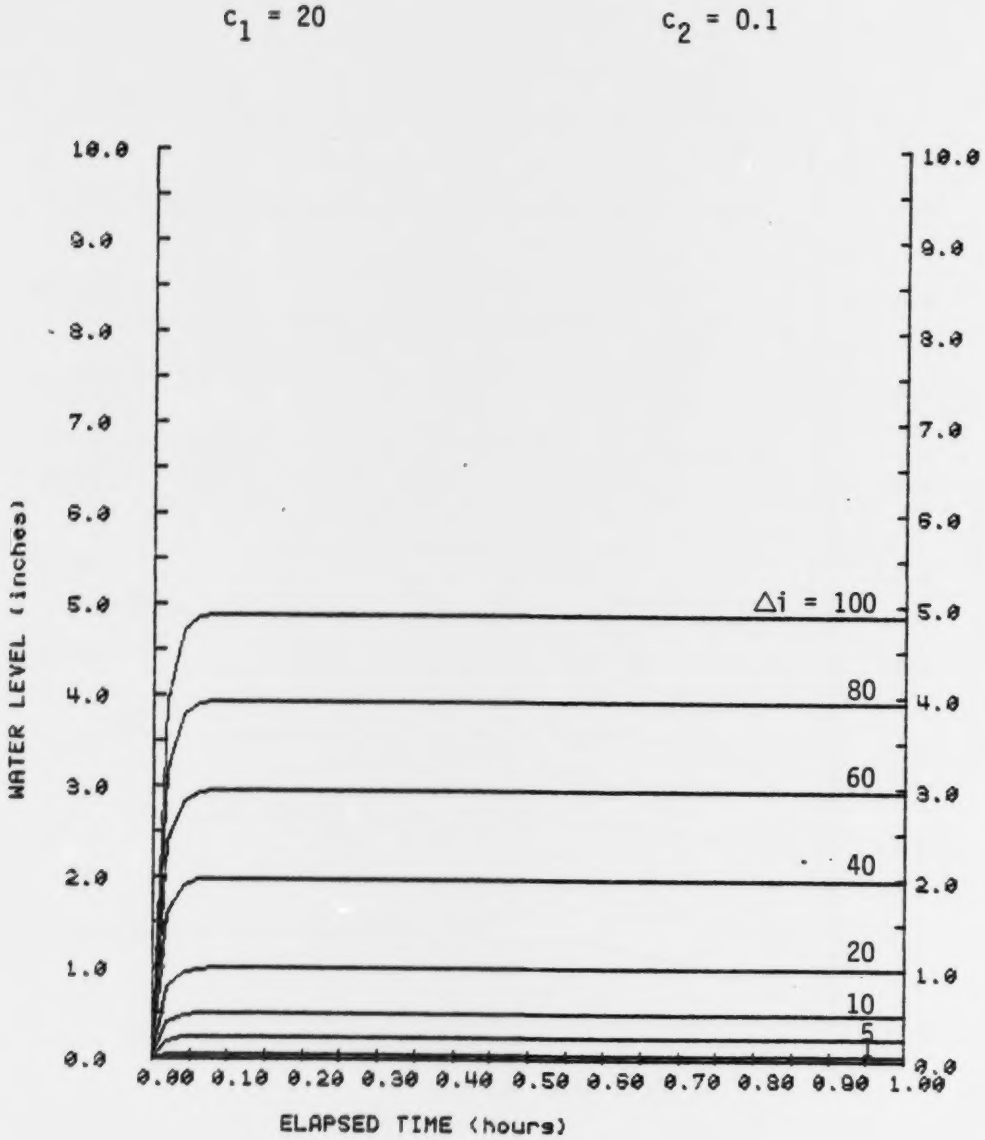


Fig. D8. Water level in the base layer during filling.

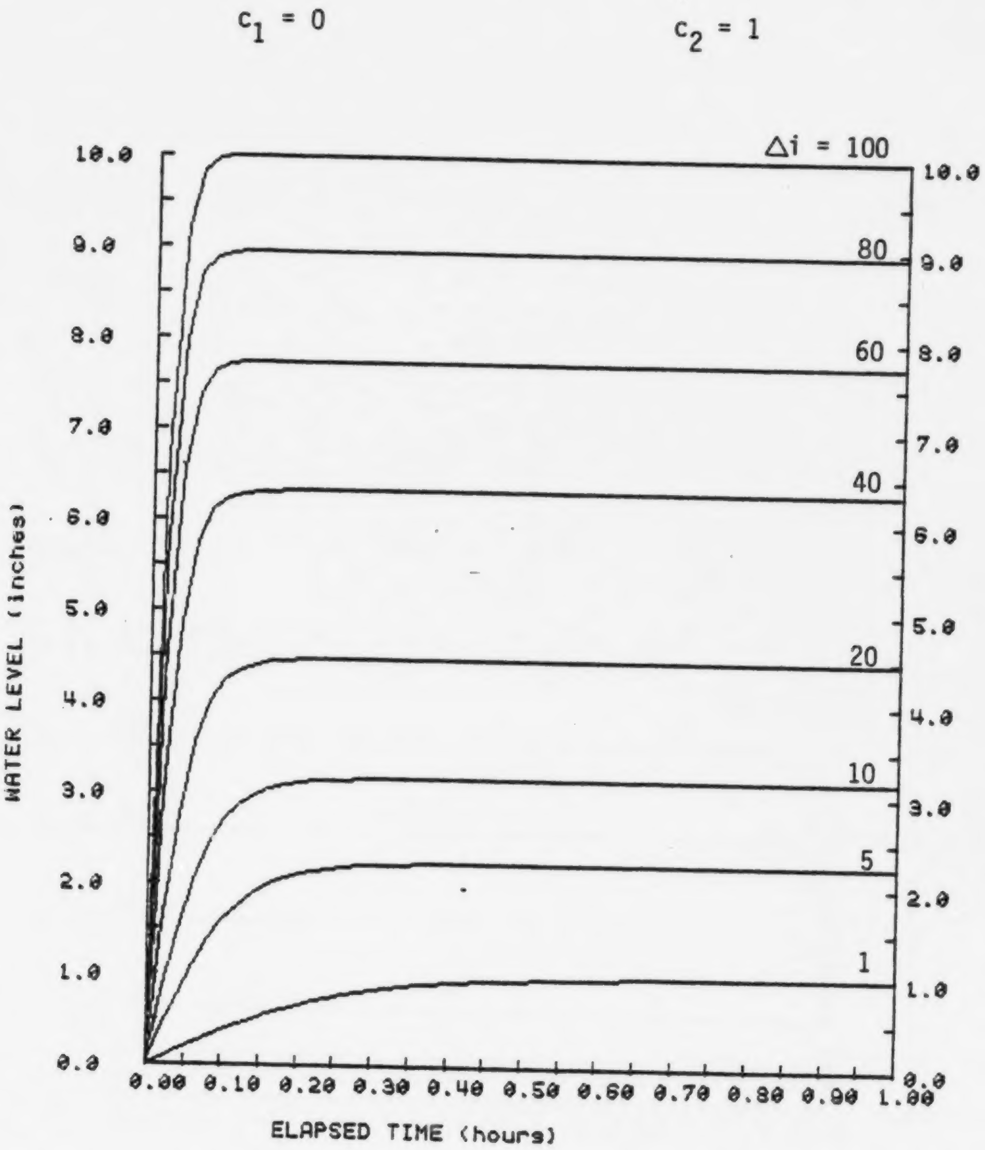


Fig. D9. Water level in the base layer during filling.

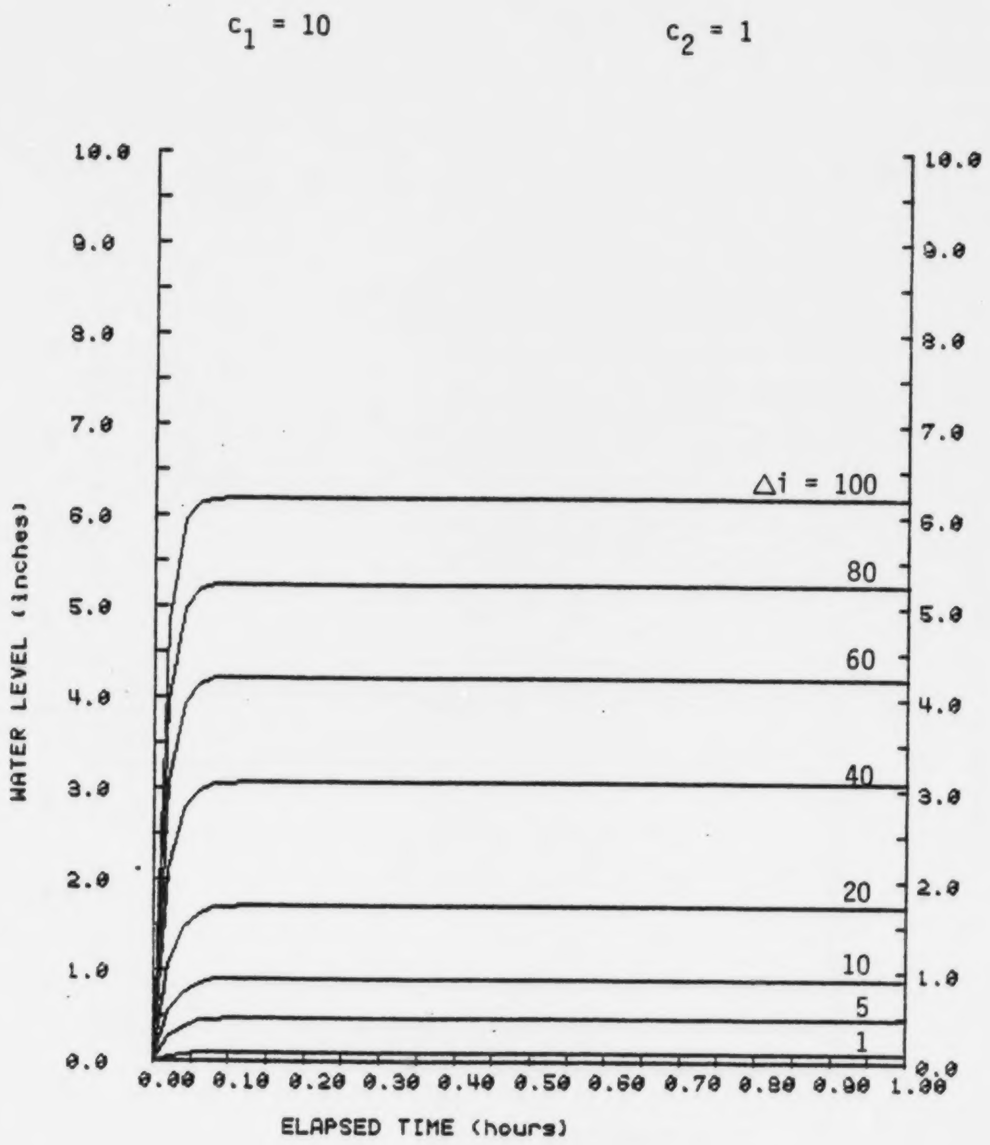


Fig. D10. Water level in the base layer during filling.

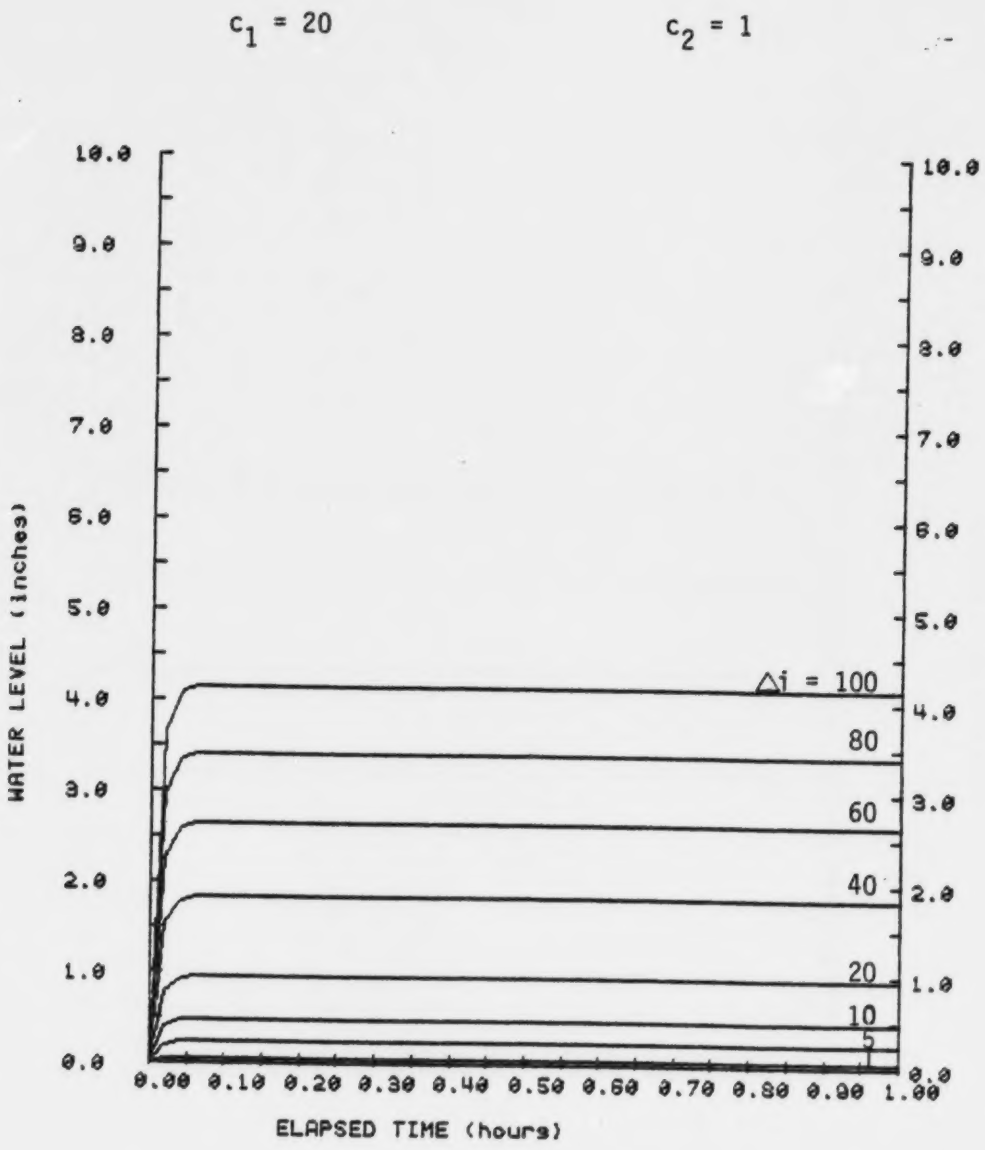


Fig. D11. Water level in the base layer during filling.

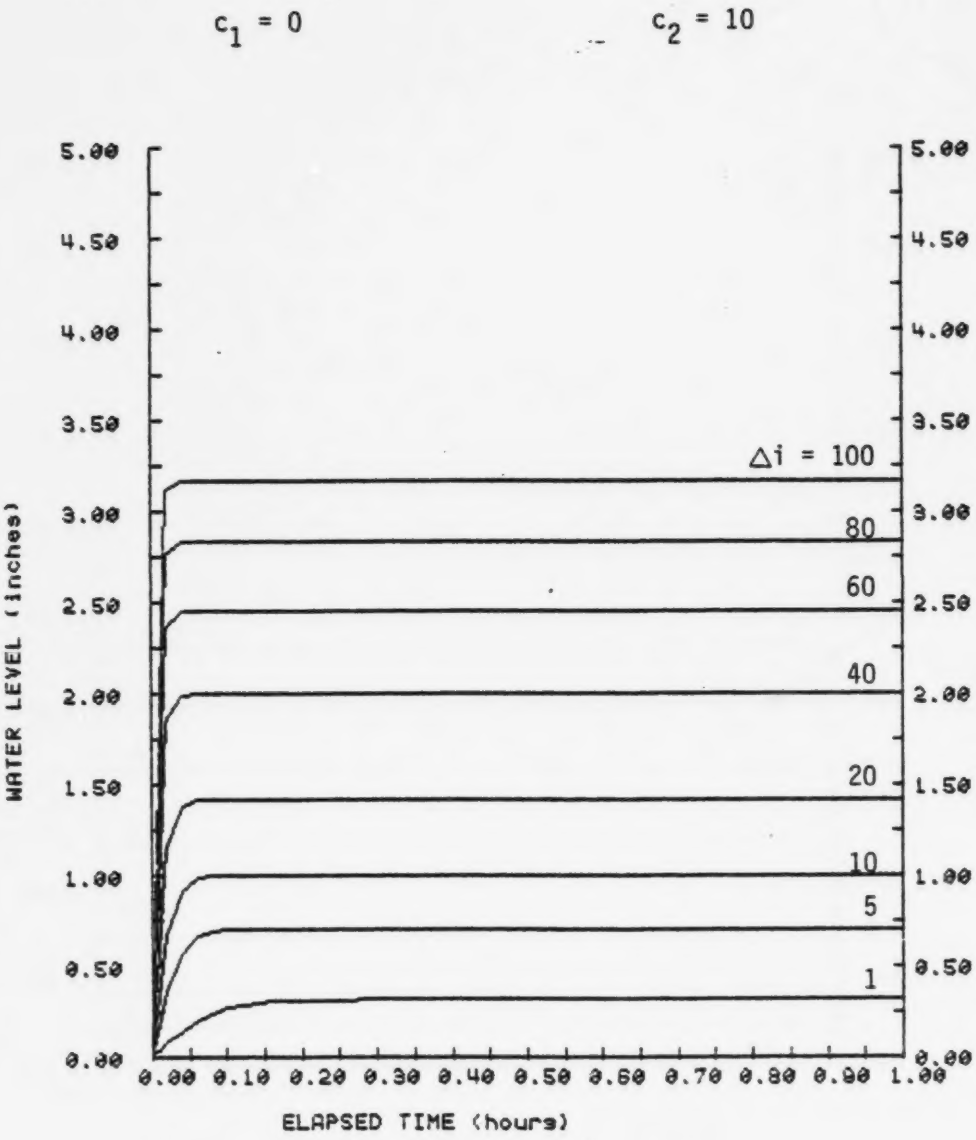


Fig. D12. Water level in the base layer during filling.

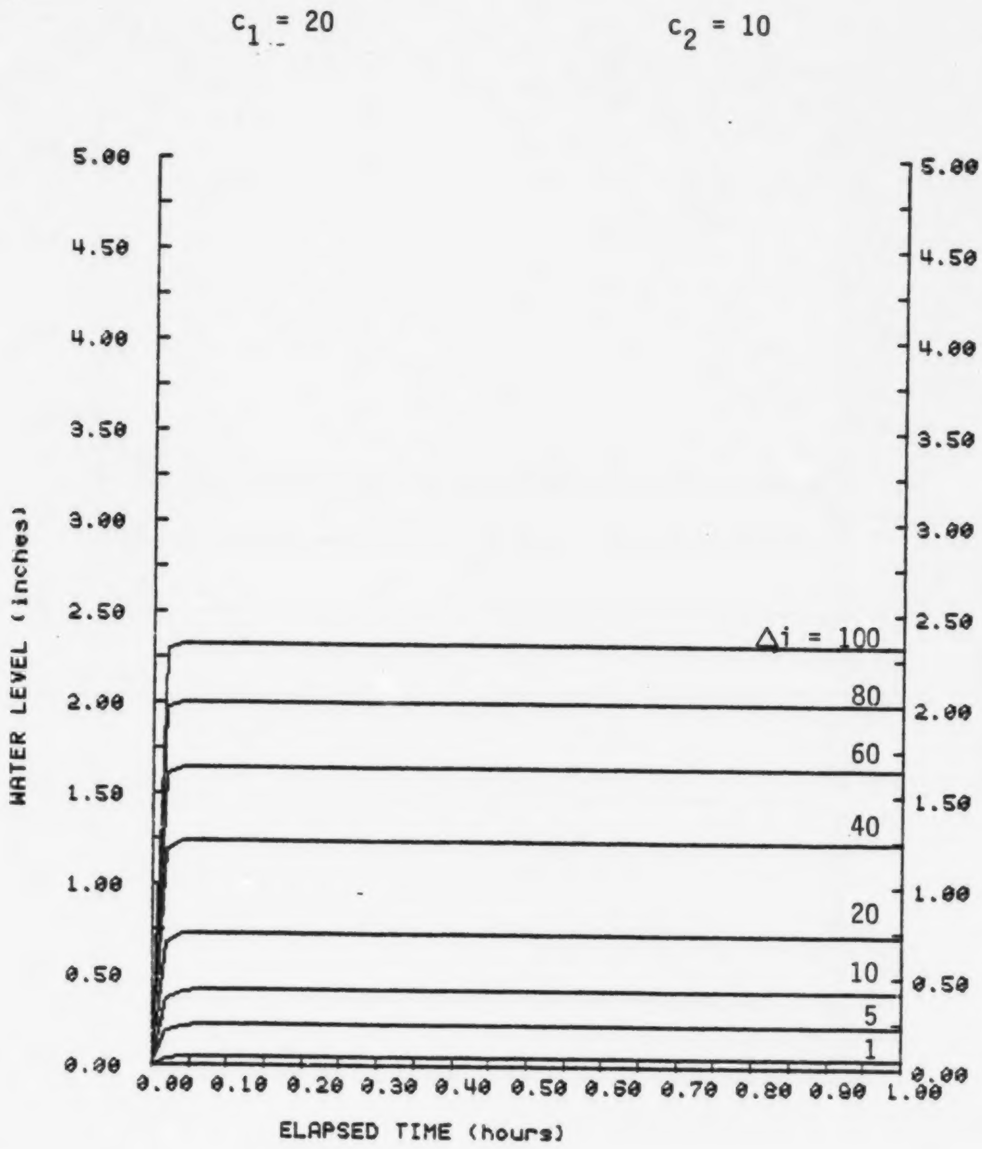


Fig. D13. Water level in the base layer during filling.

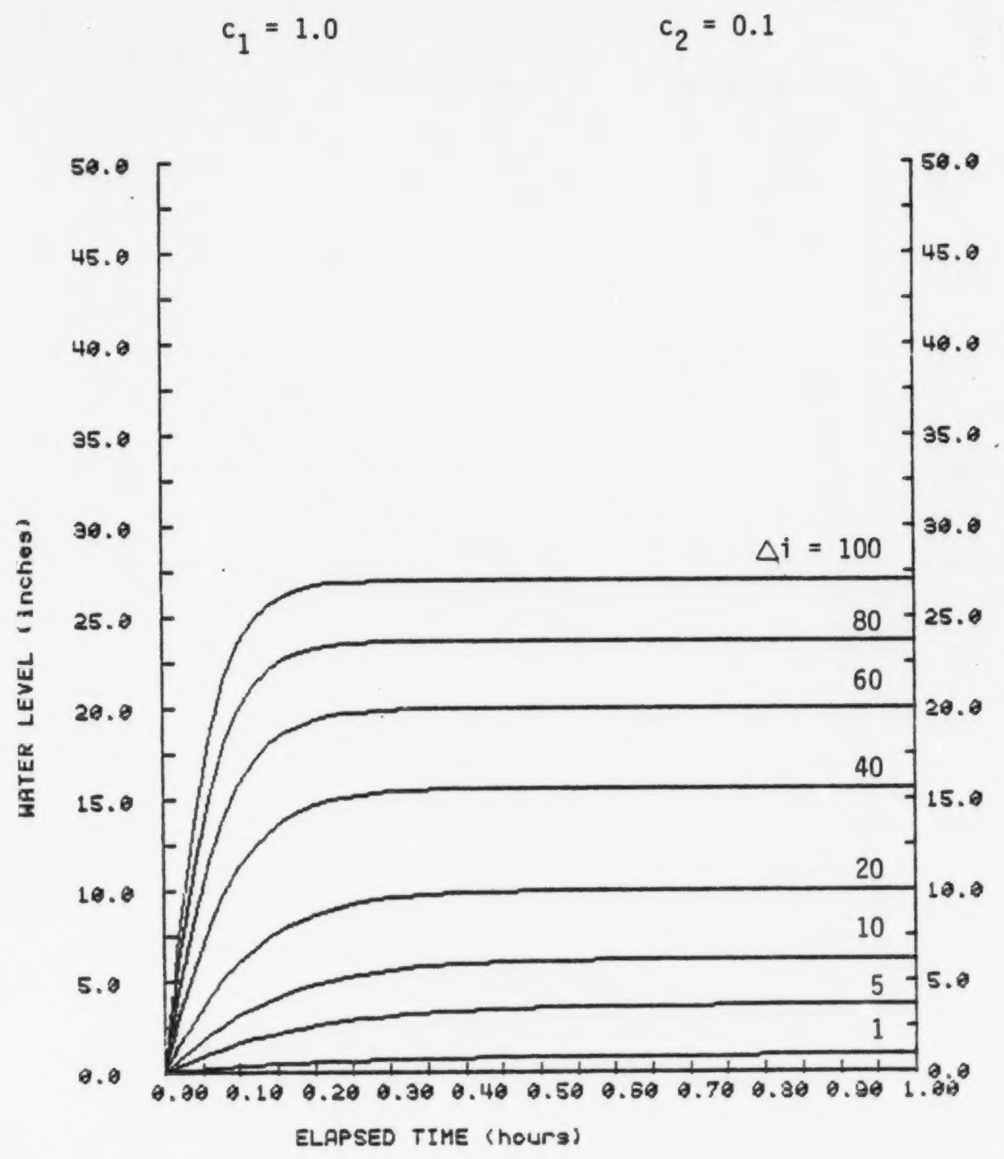


Fig. D14. Water level in the base layer during filling.

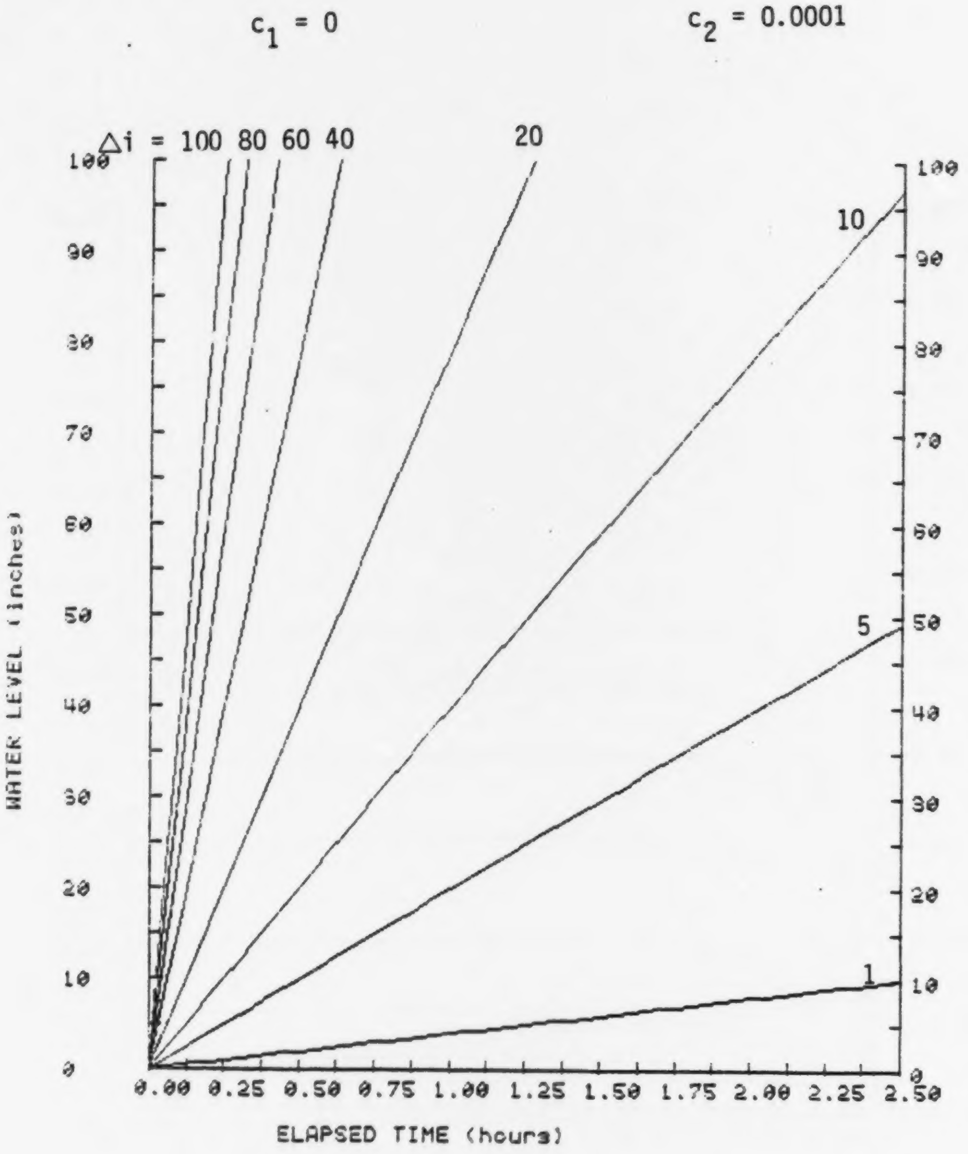


Fig. D15. **Water level in the base layer during filling.**

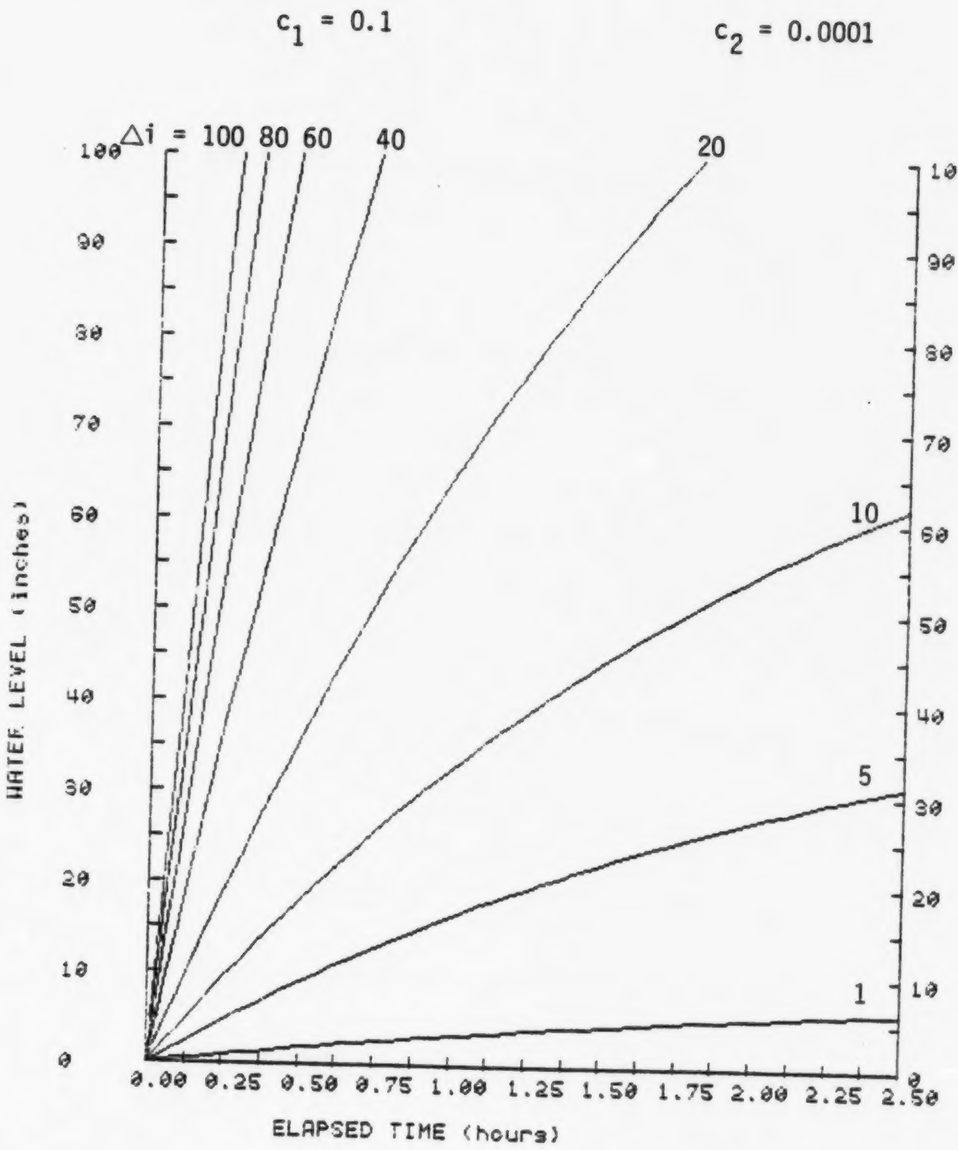


Fig. D16. Water level in the base layer during filling.

$c_1 = 1.0$ $c_2 = 0.0001$

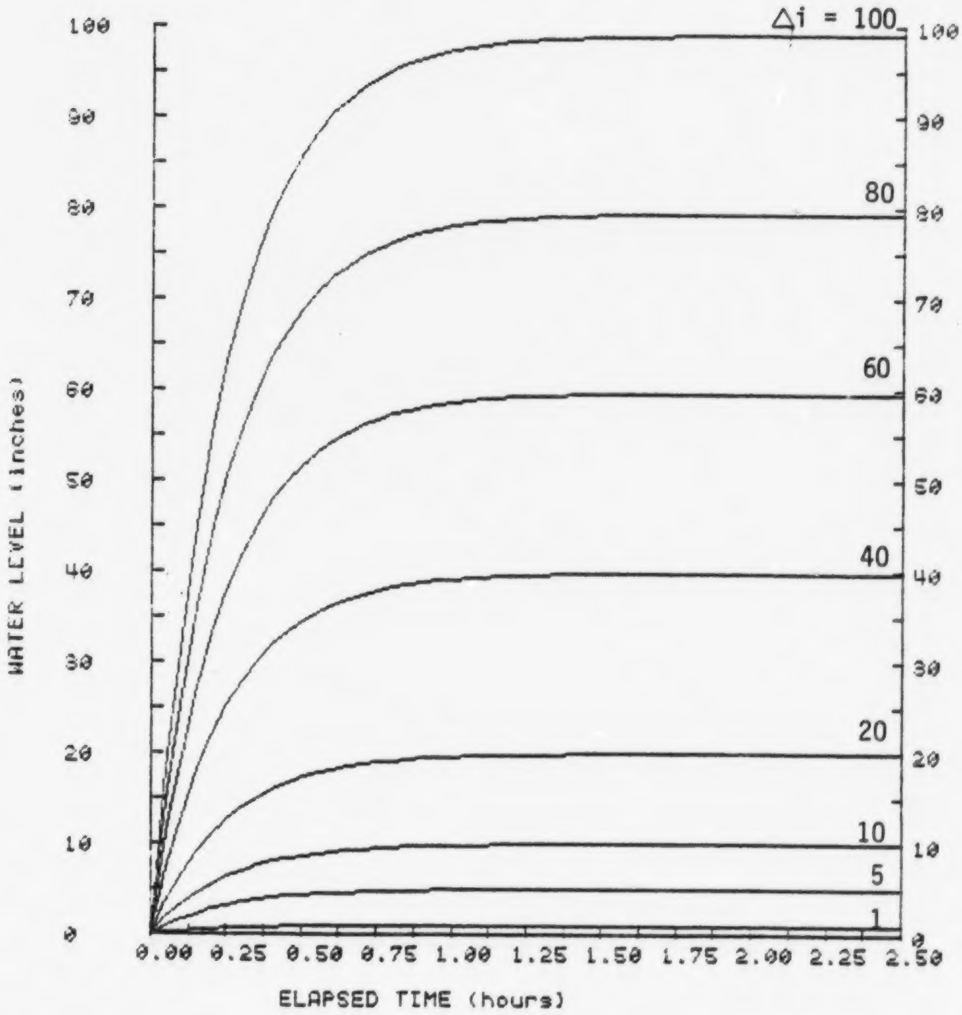


Fig. D17. Water level in the base layer during filling.

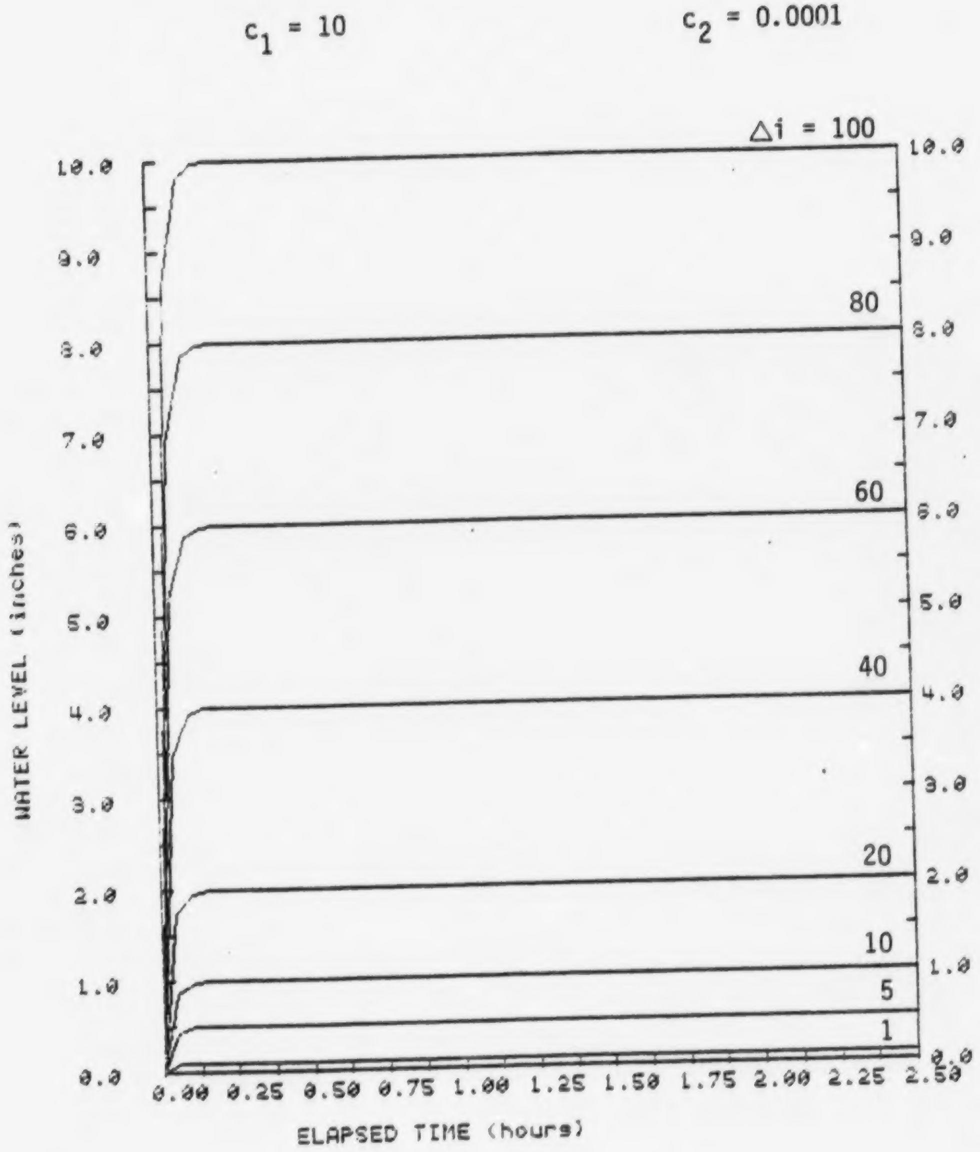


Fig. D18. Water level in the base layer during filling.

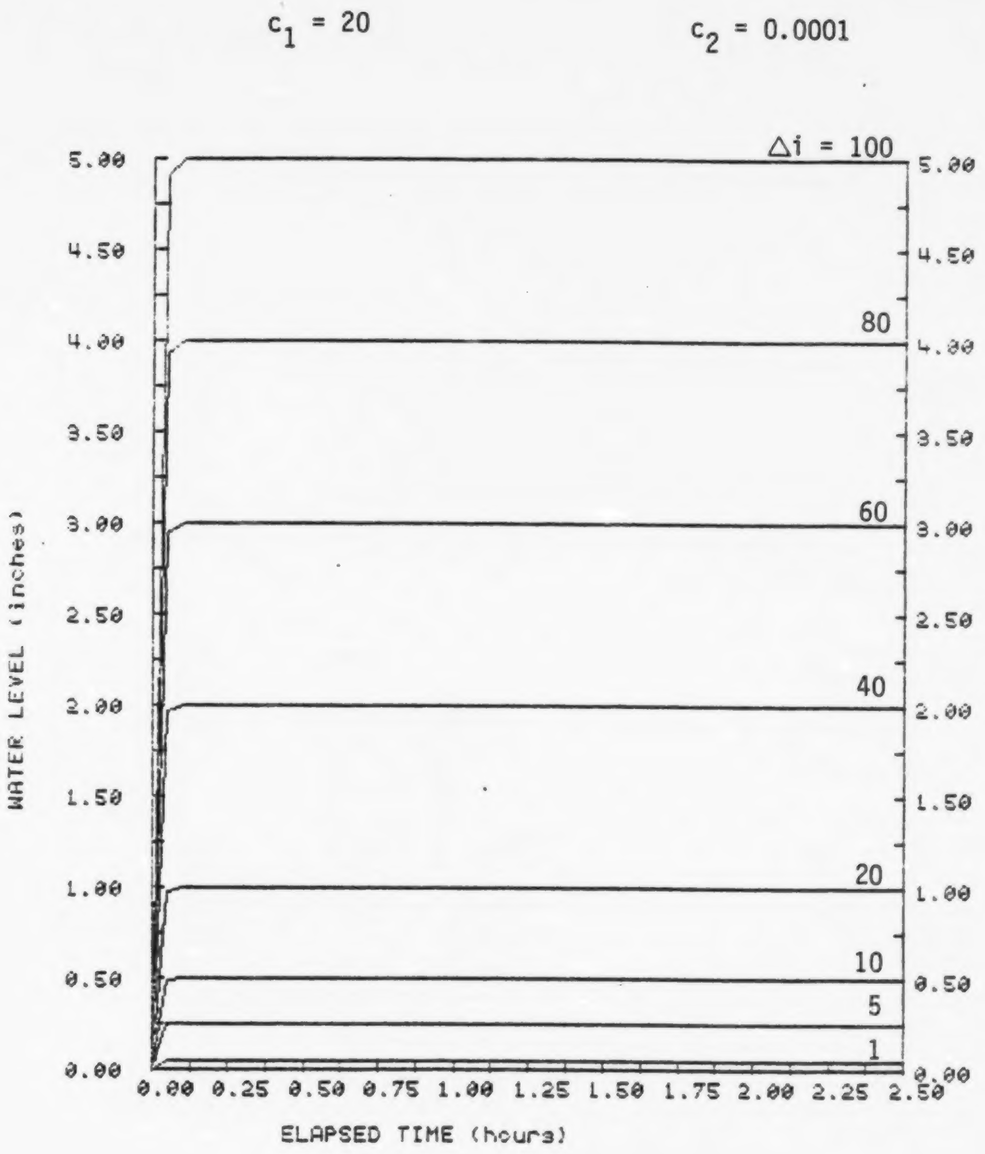


Fig. D19. Water level in the base layer during filling.

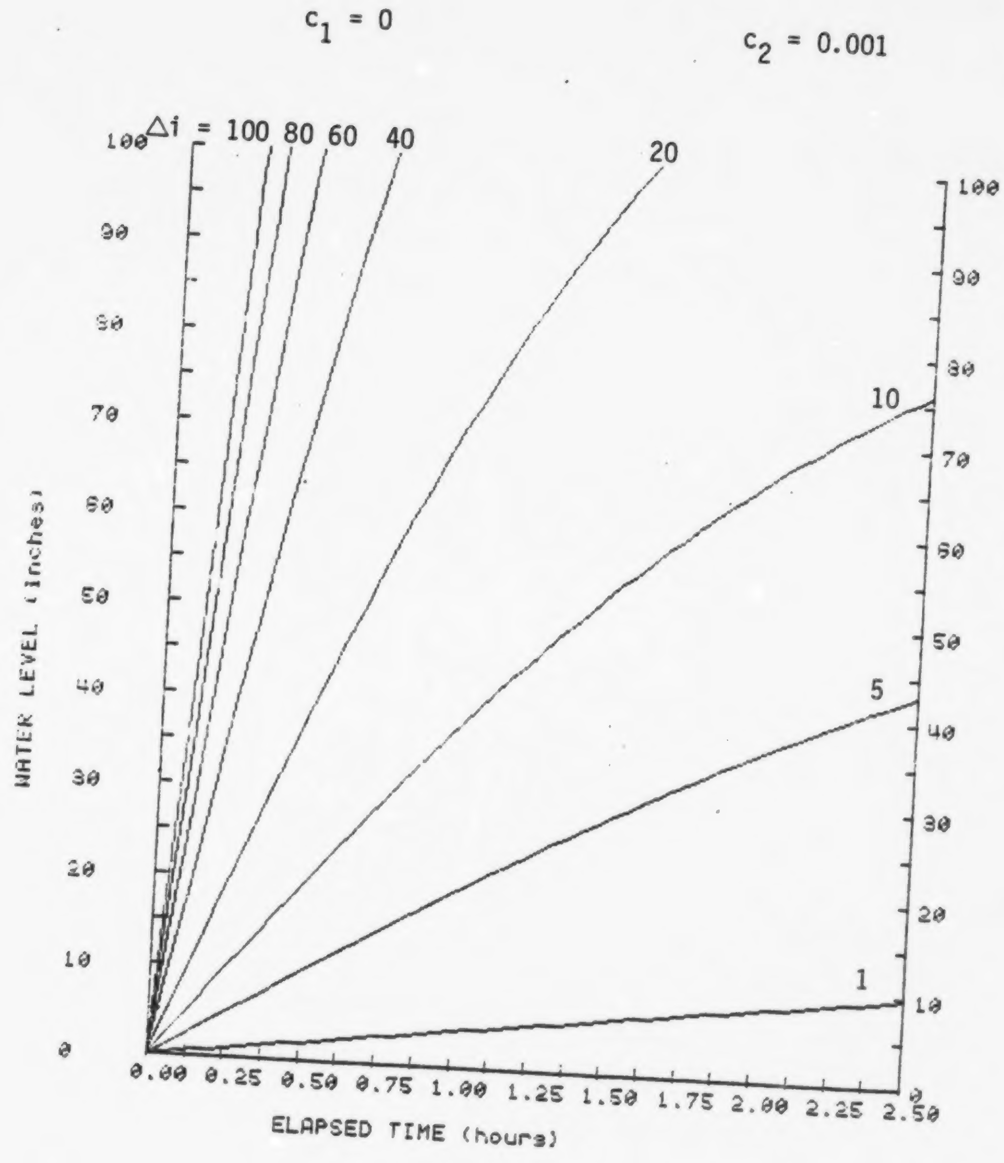


Fig. D20. Water level in the base layer during filling.

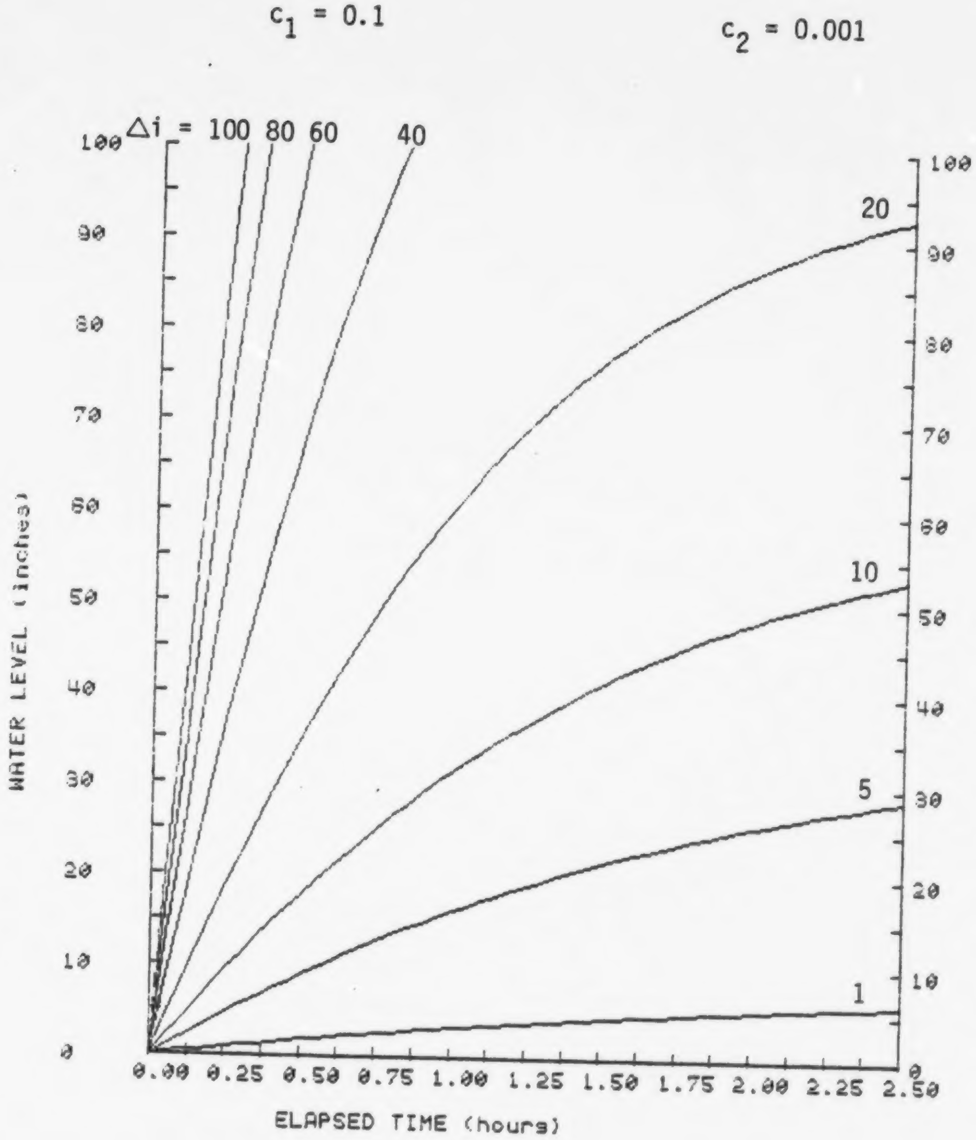


Fig. D21. Water level in the base layer during filling.

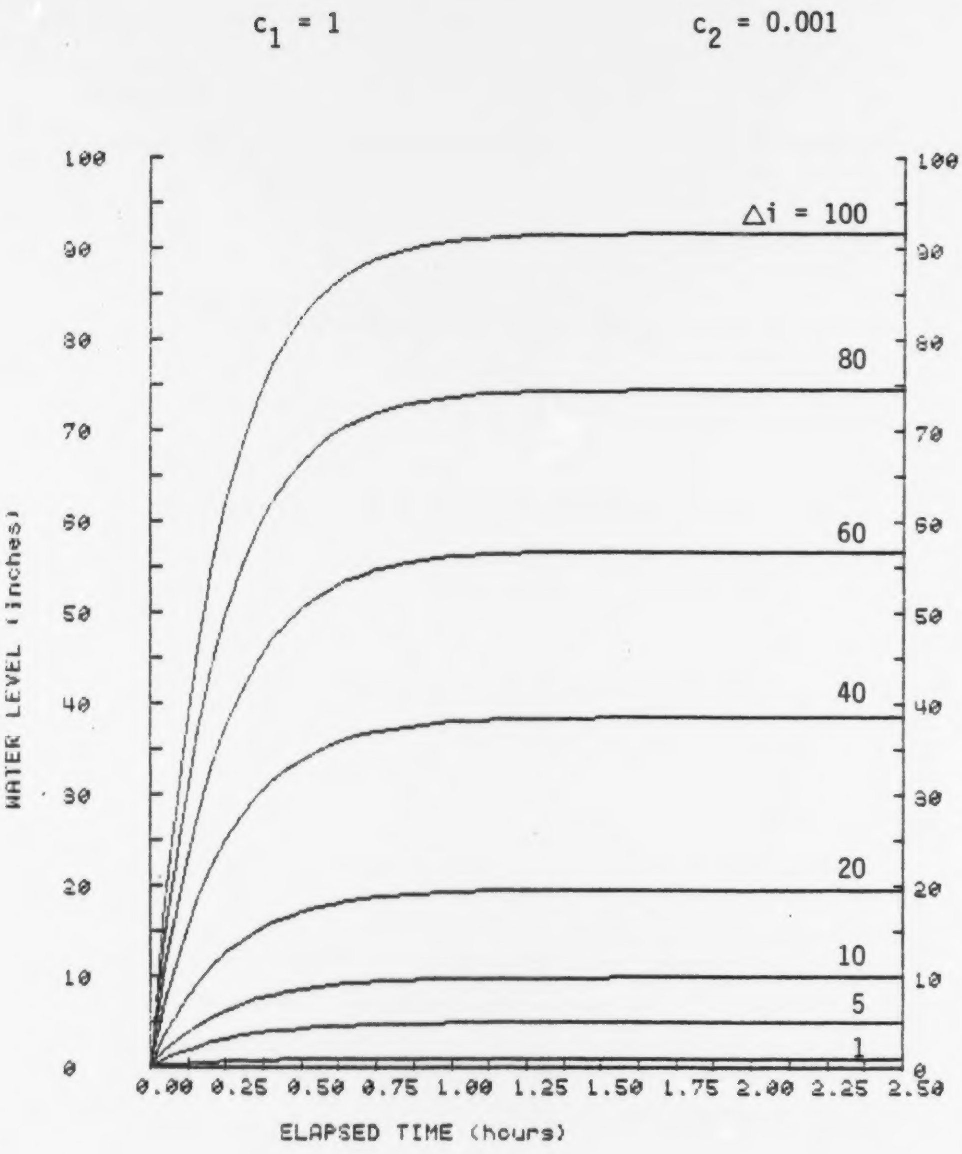


Fig. D22. Water level in the base layer during filling.

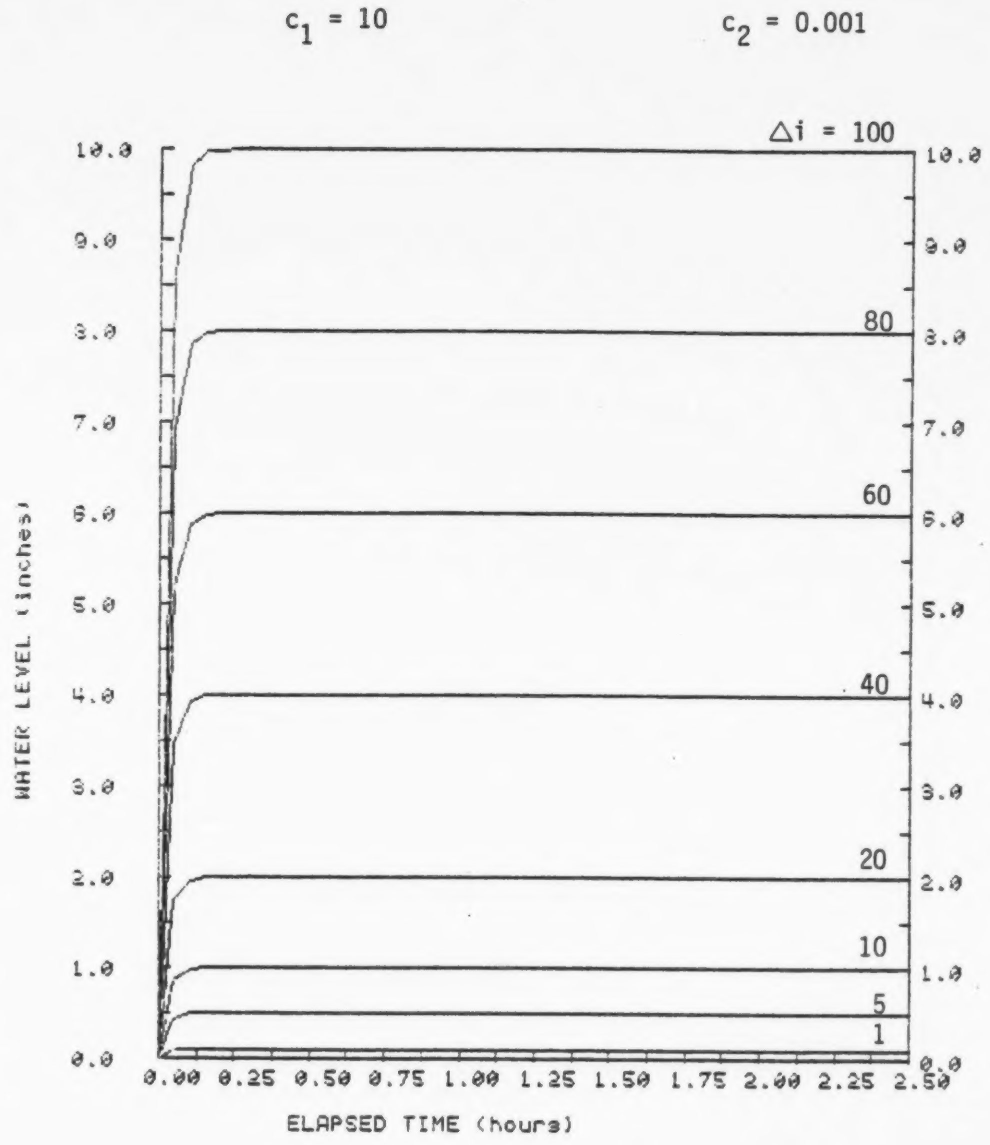


Fig. D23. Water level in the base layer during filling.

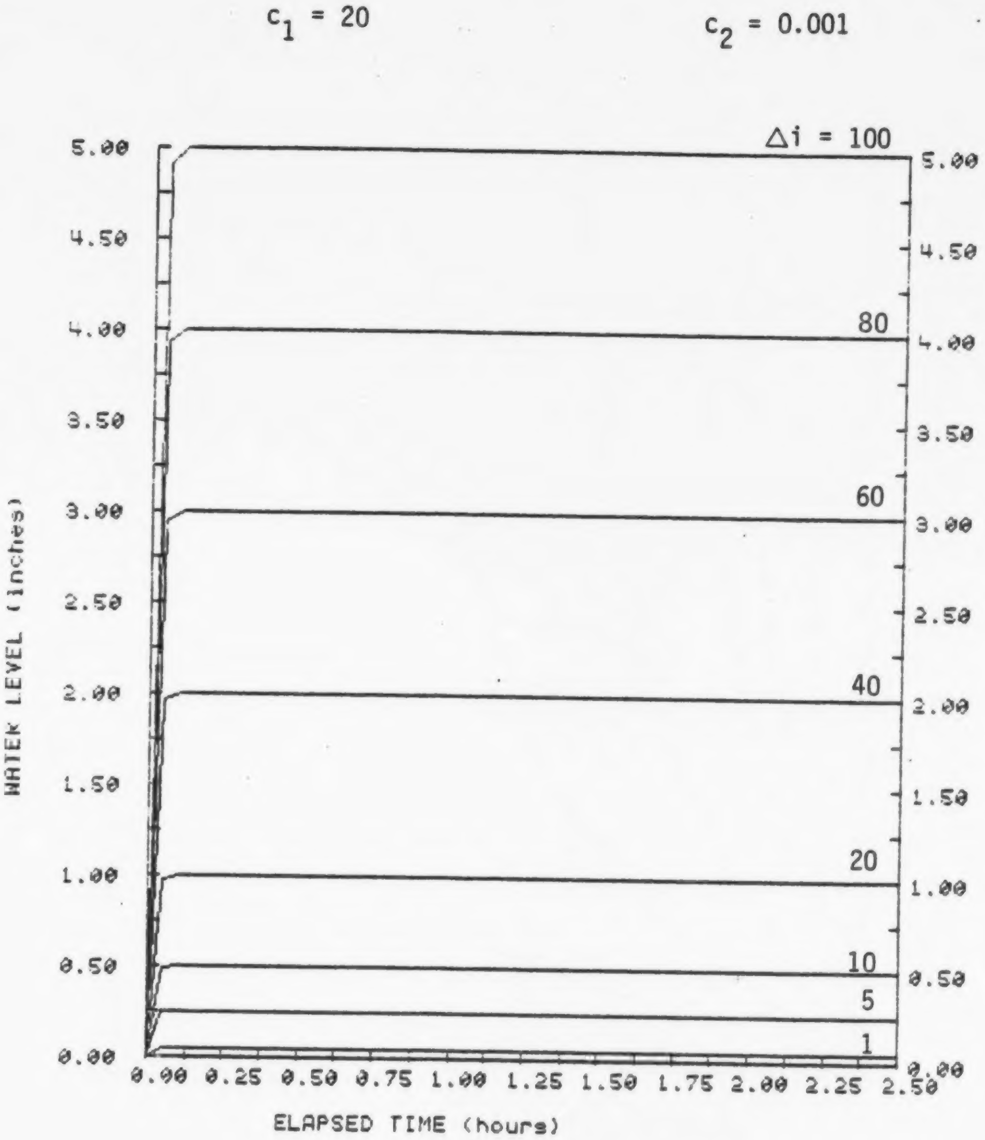


Fig. D24. Water level in the base layer during filling.

APPENDIX E. WATER LEVEL IN THE BASE LAYER DURING DRAINING

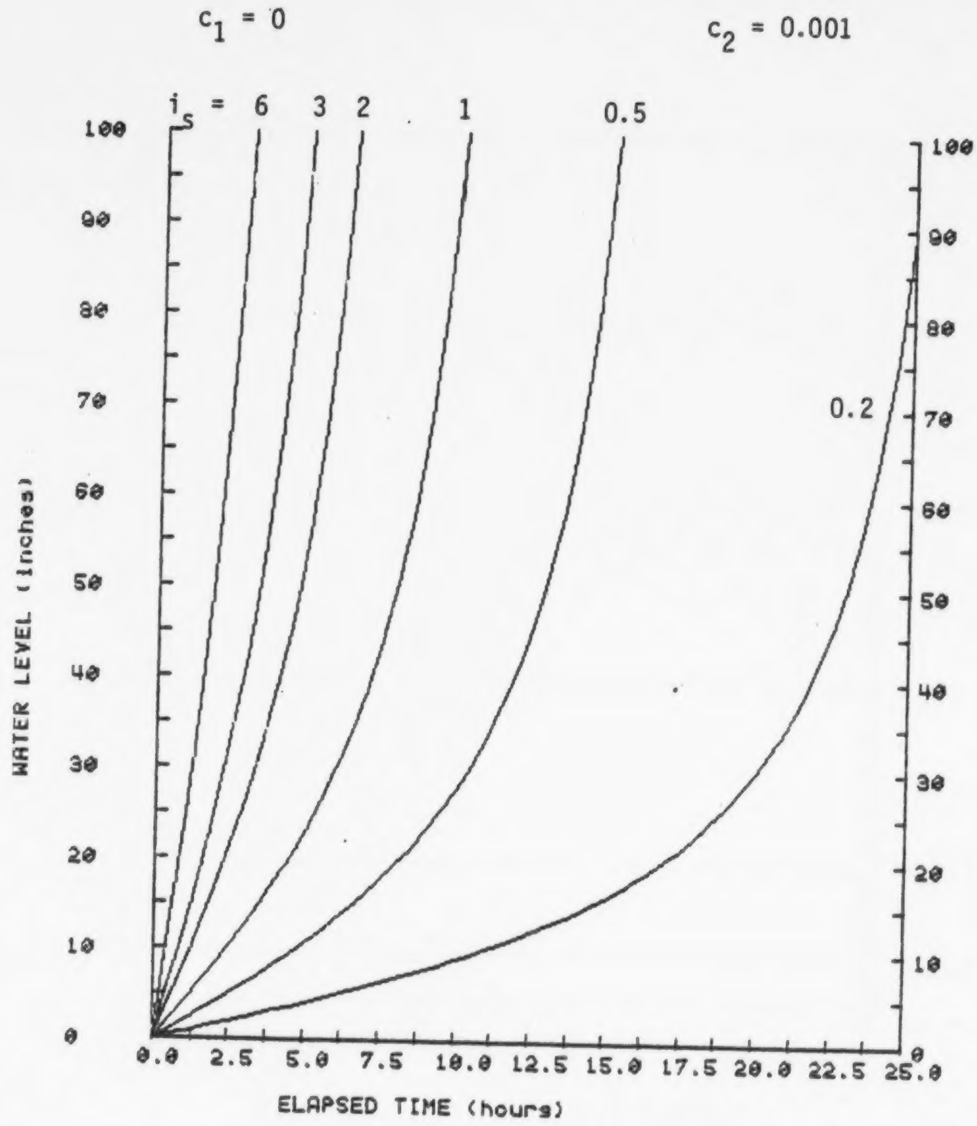


Fig. E1. Water level in the base layer during draining.

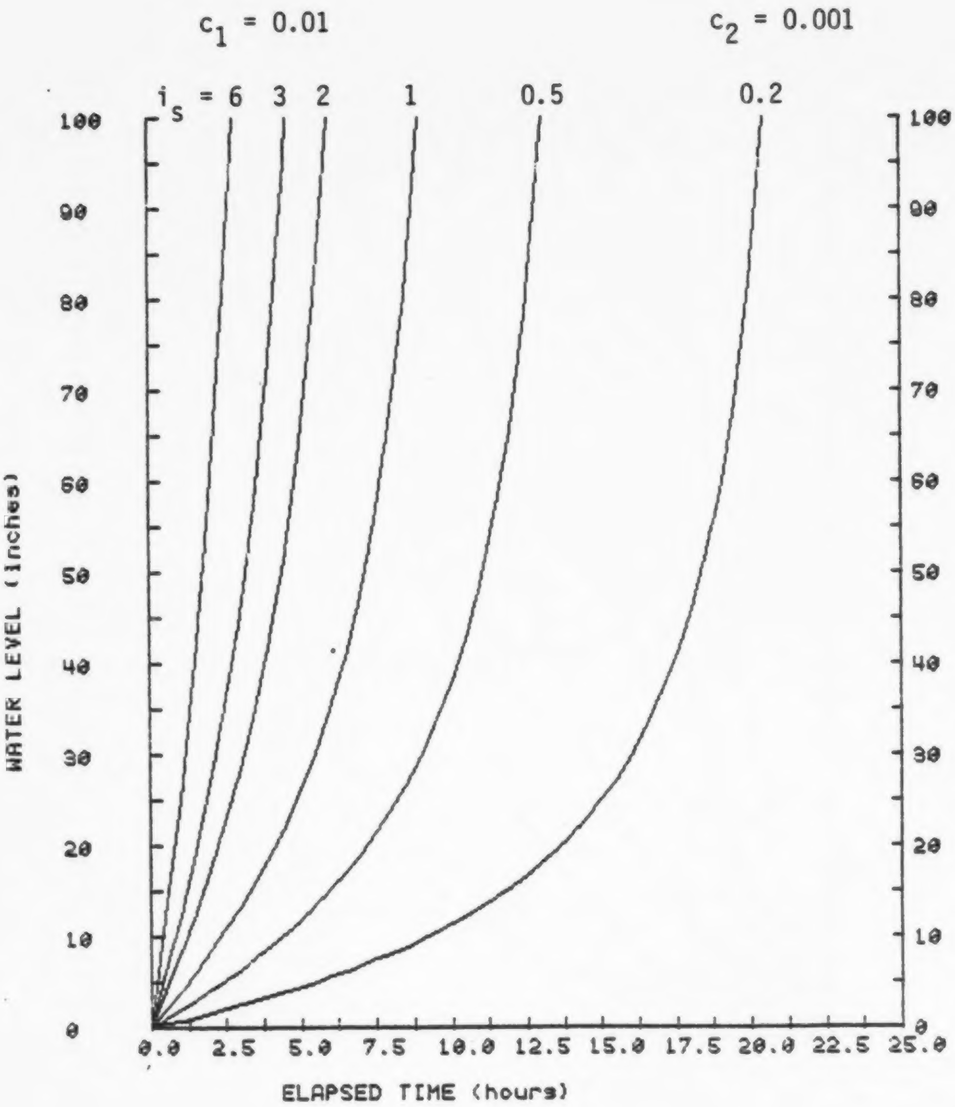


Fig. E2. Water level in the base layer during draining.

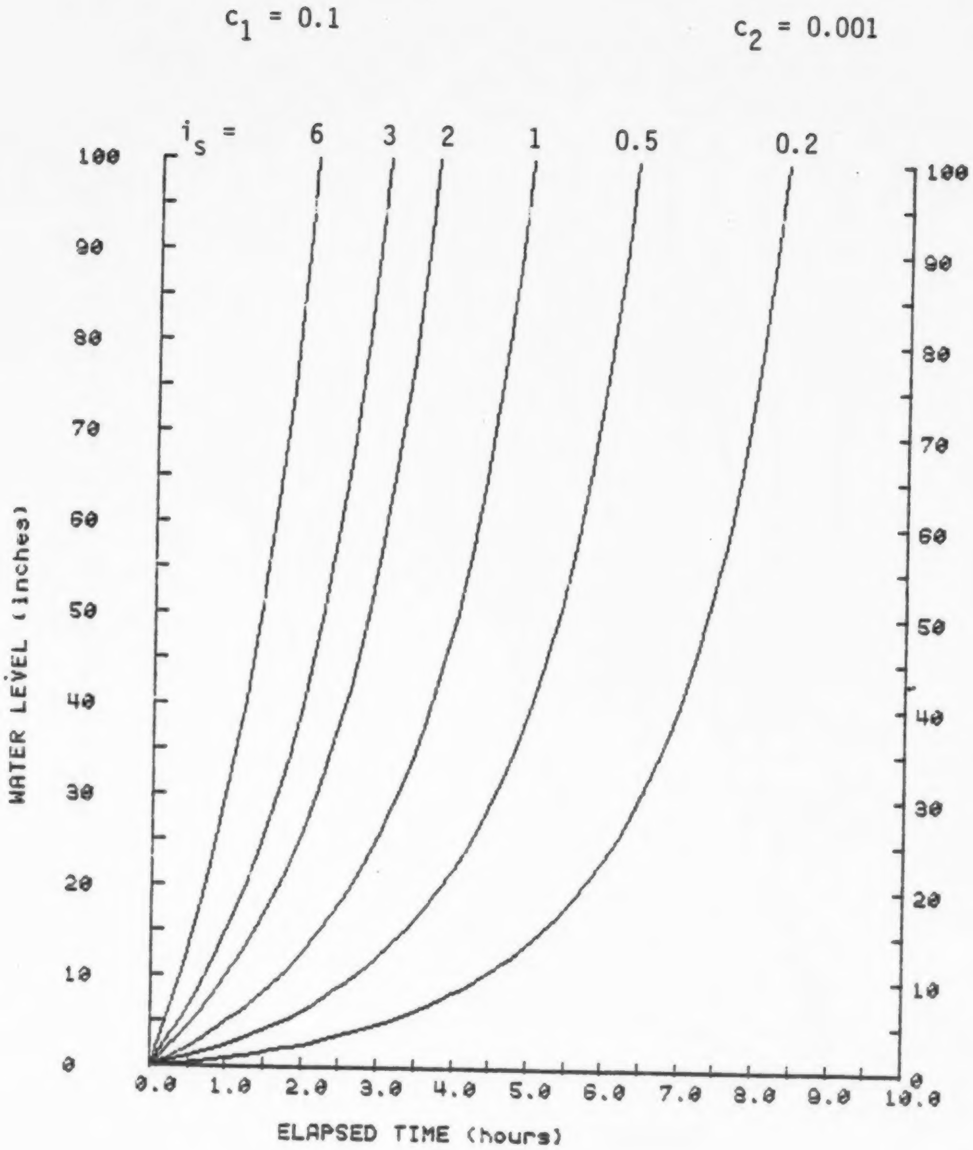


Fig. E3. Water level in the base layer during draining.

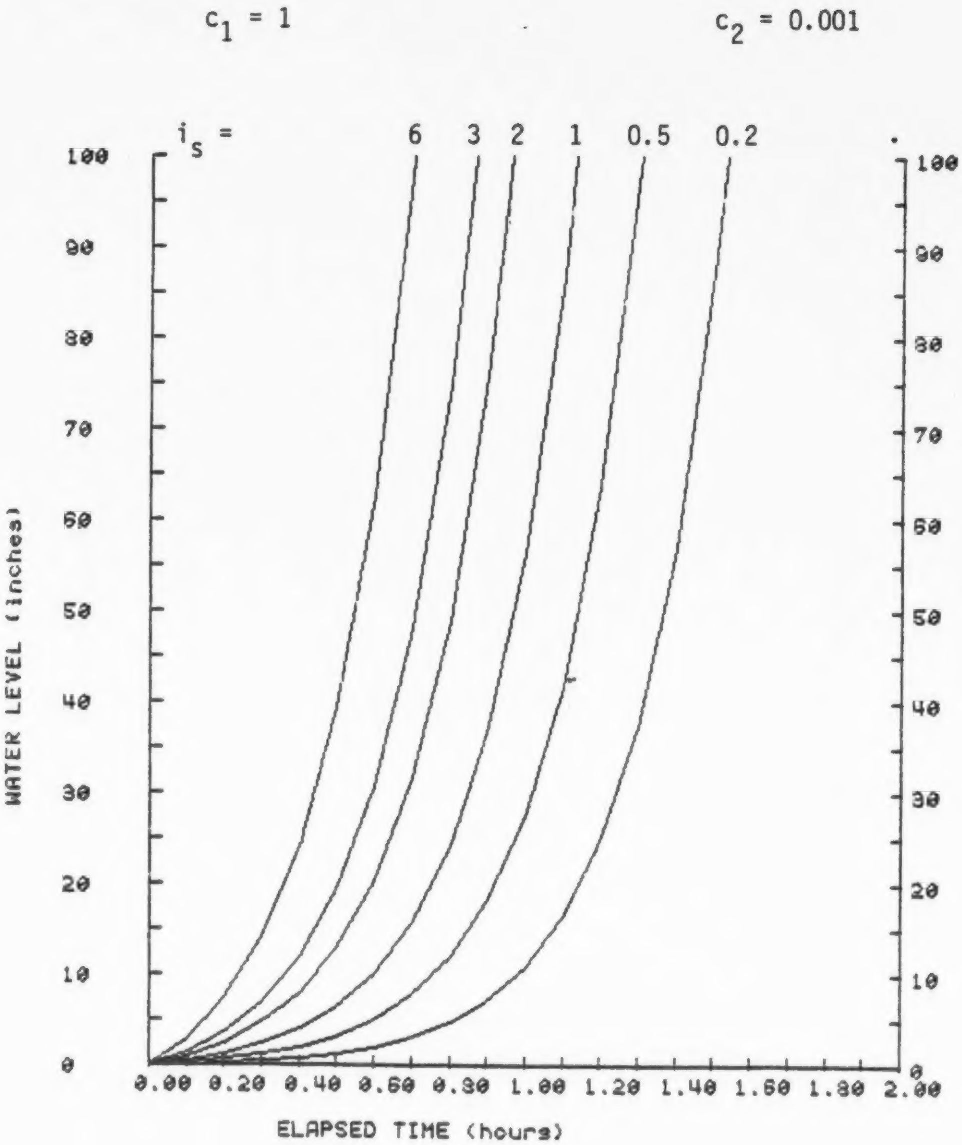


Fig. E4. Water level in the base layer during draining.

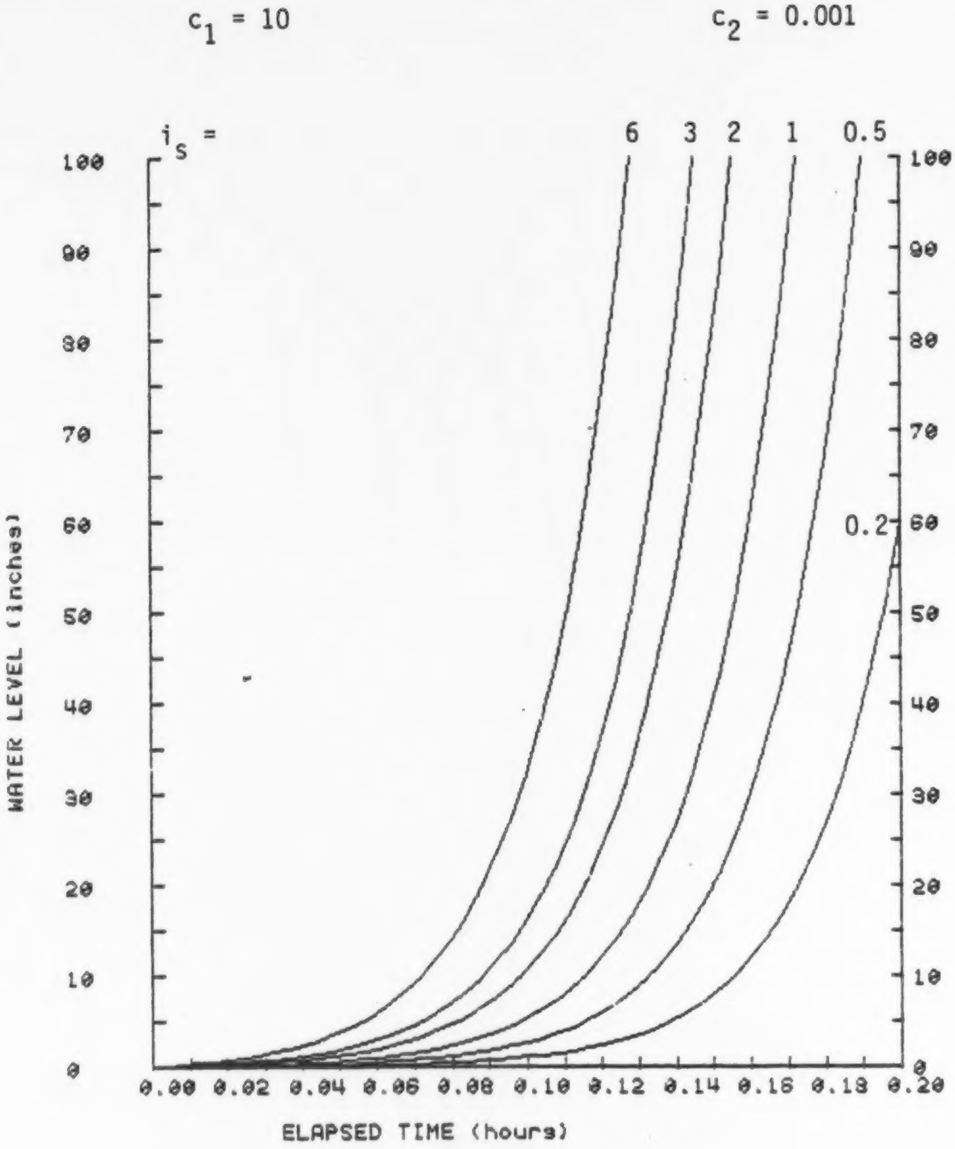


Fig. E5. Water Level in the base layer during draining.

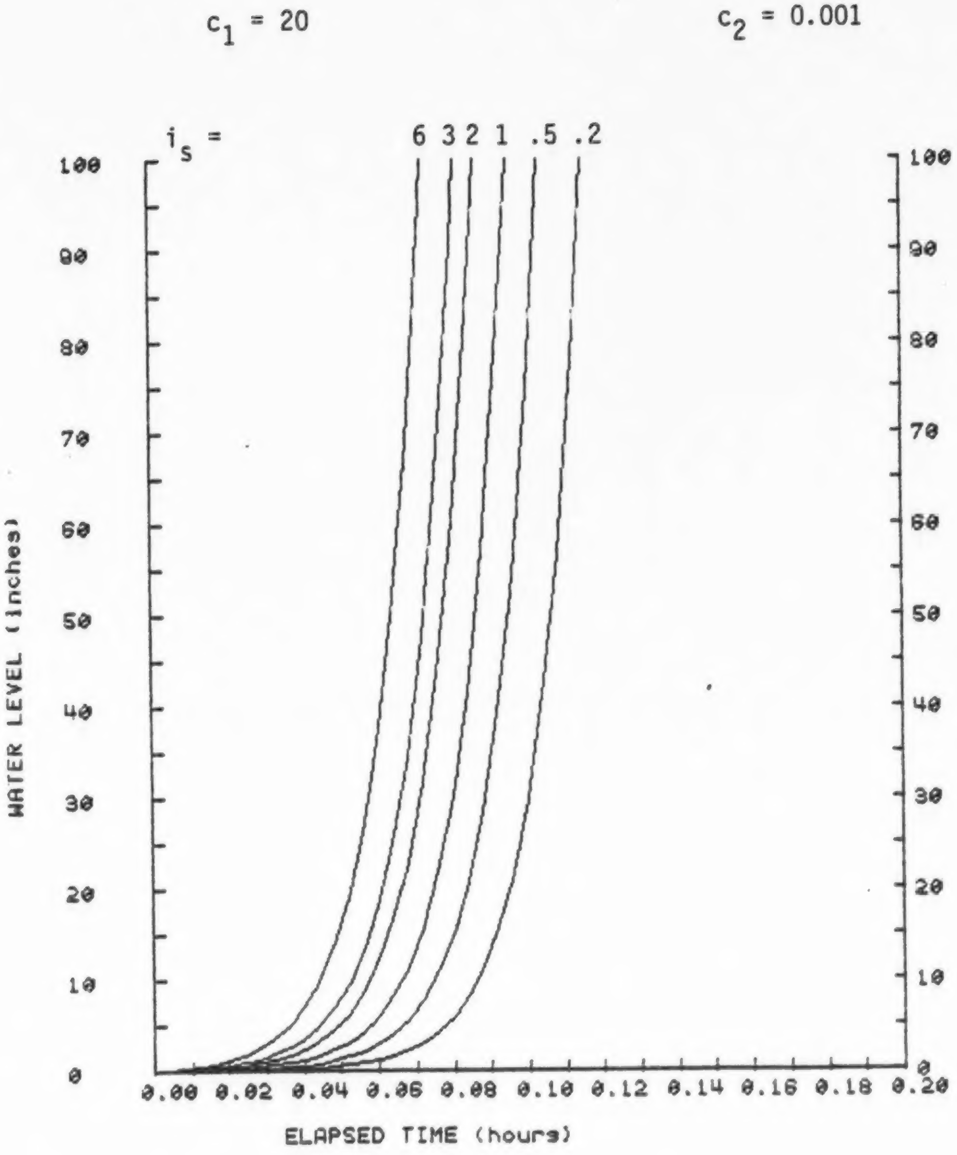


Fig. E6. Water level in the base layer during draining.

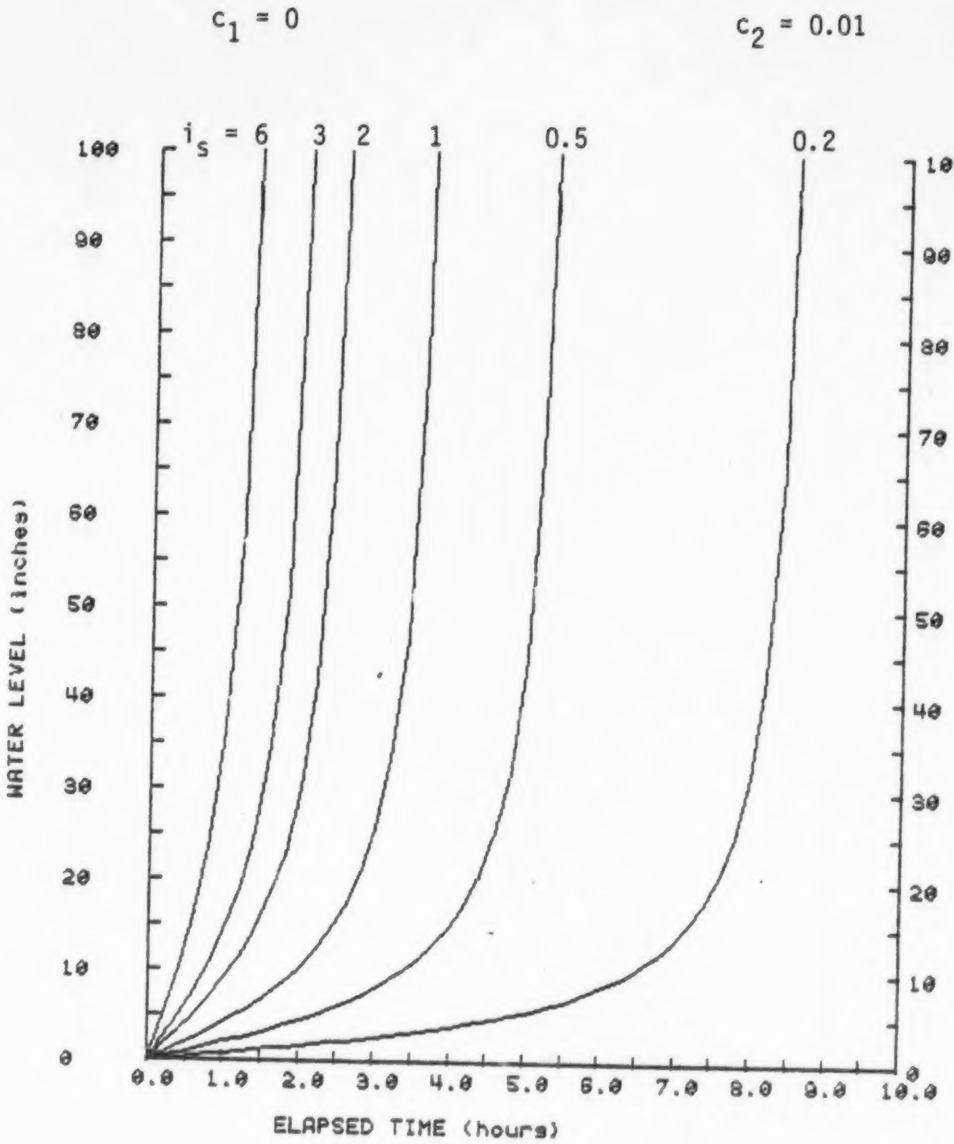


Fig. E7. Water level in the base layer during draining.

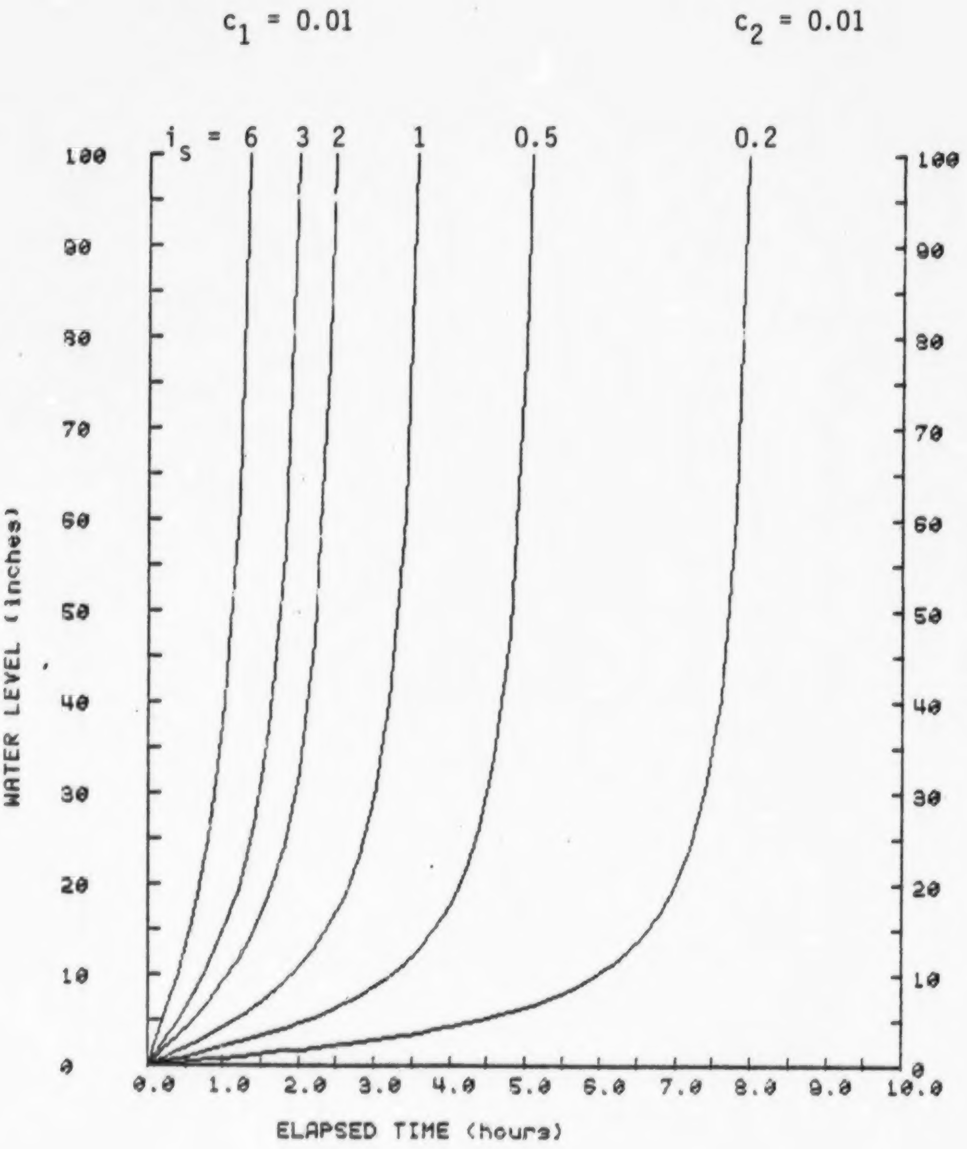


Fig. E8. Water level in the base layer during draining.

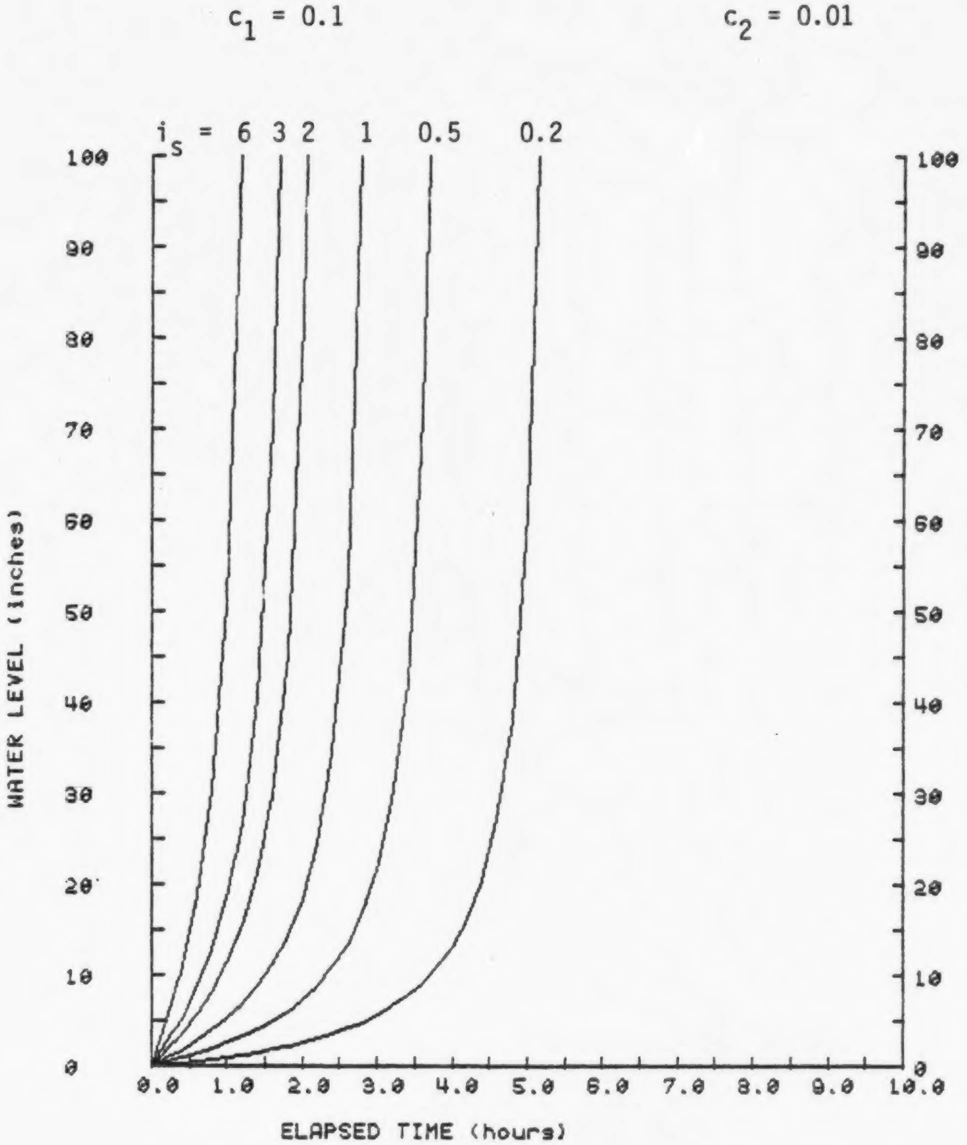


Fig. E9. Water level in the base layer during draining.

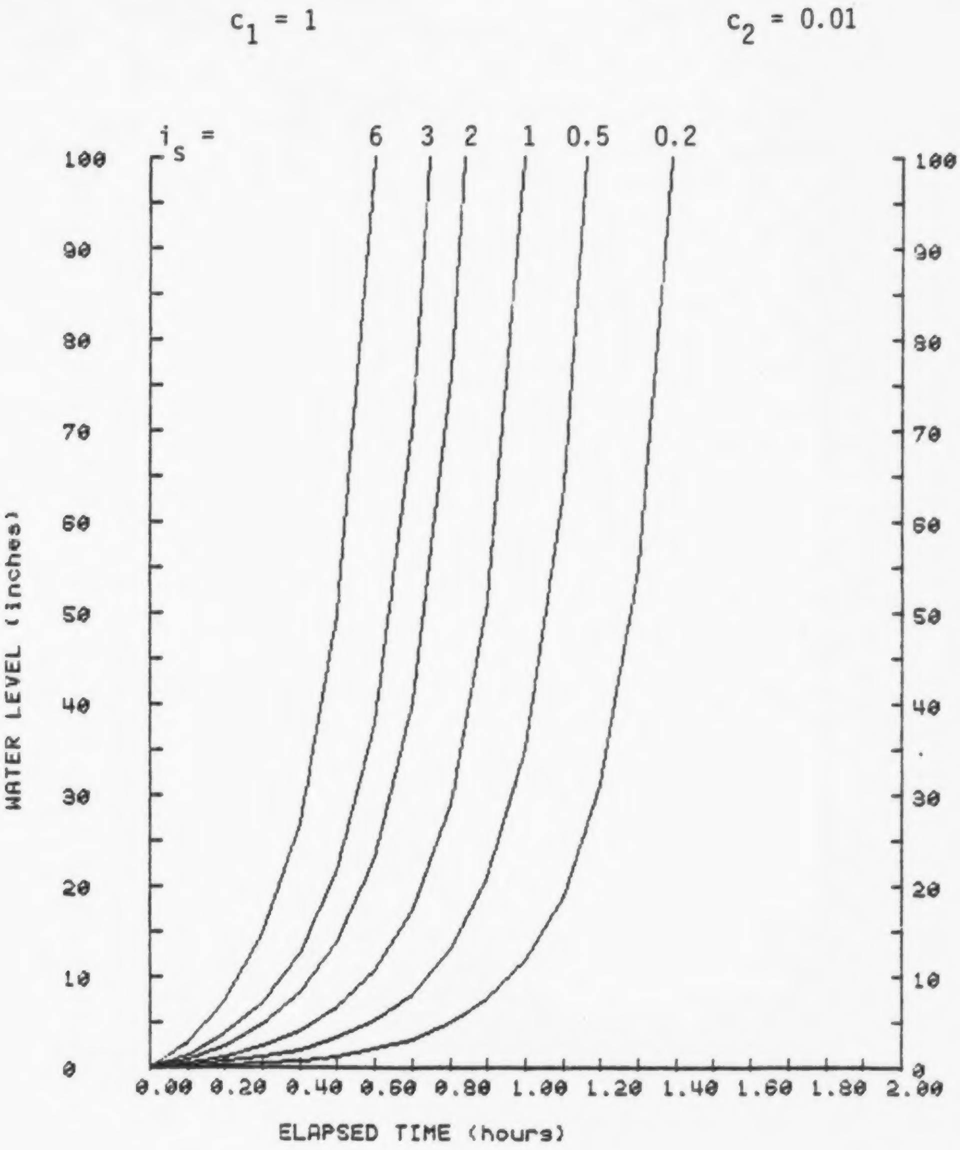


Fig. E10. Water level in the base layer during draining.

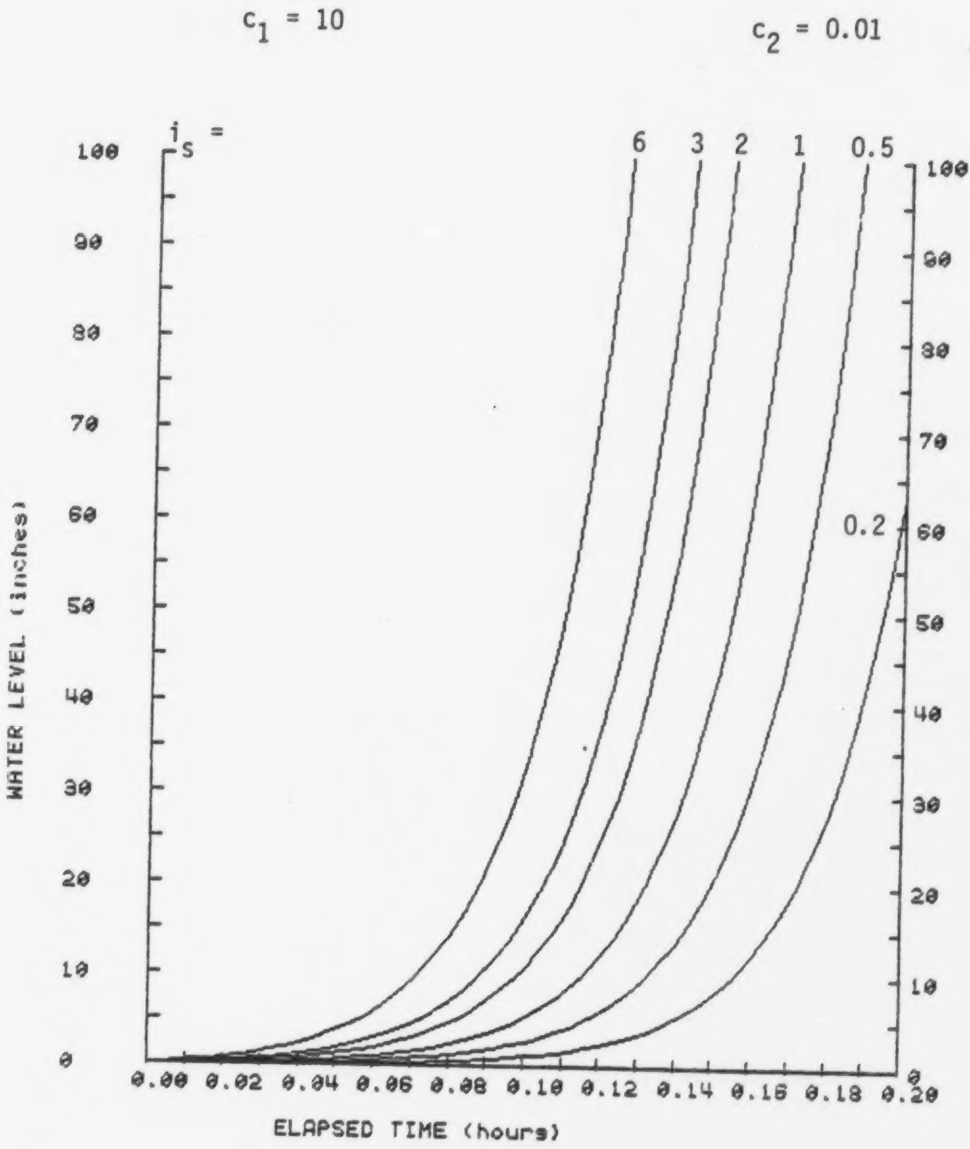


Fig. E11. Water level in the base layer during draining.

$c_1 = 20$ $c_2 = 0.01$

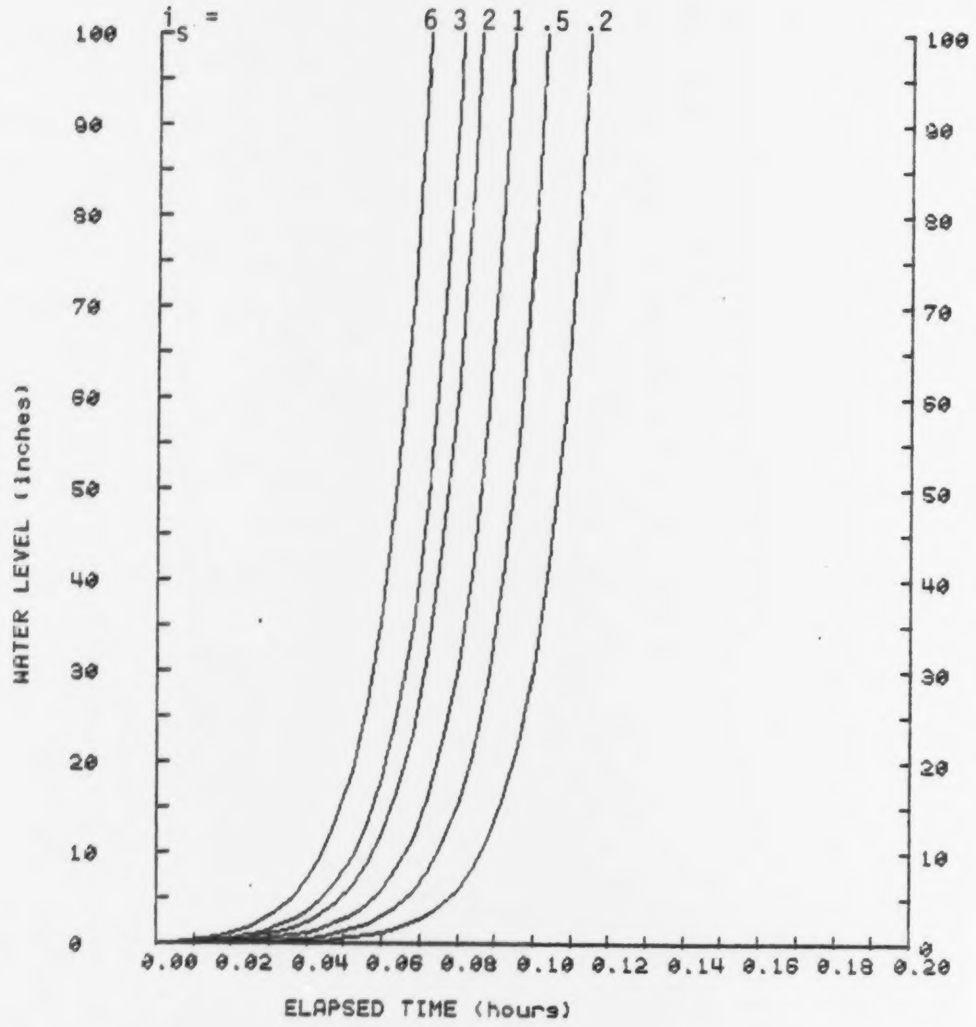


Fig. E12. Water level in the base layer during draining.

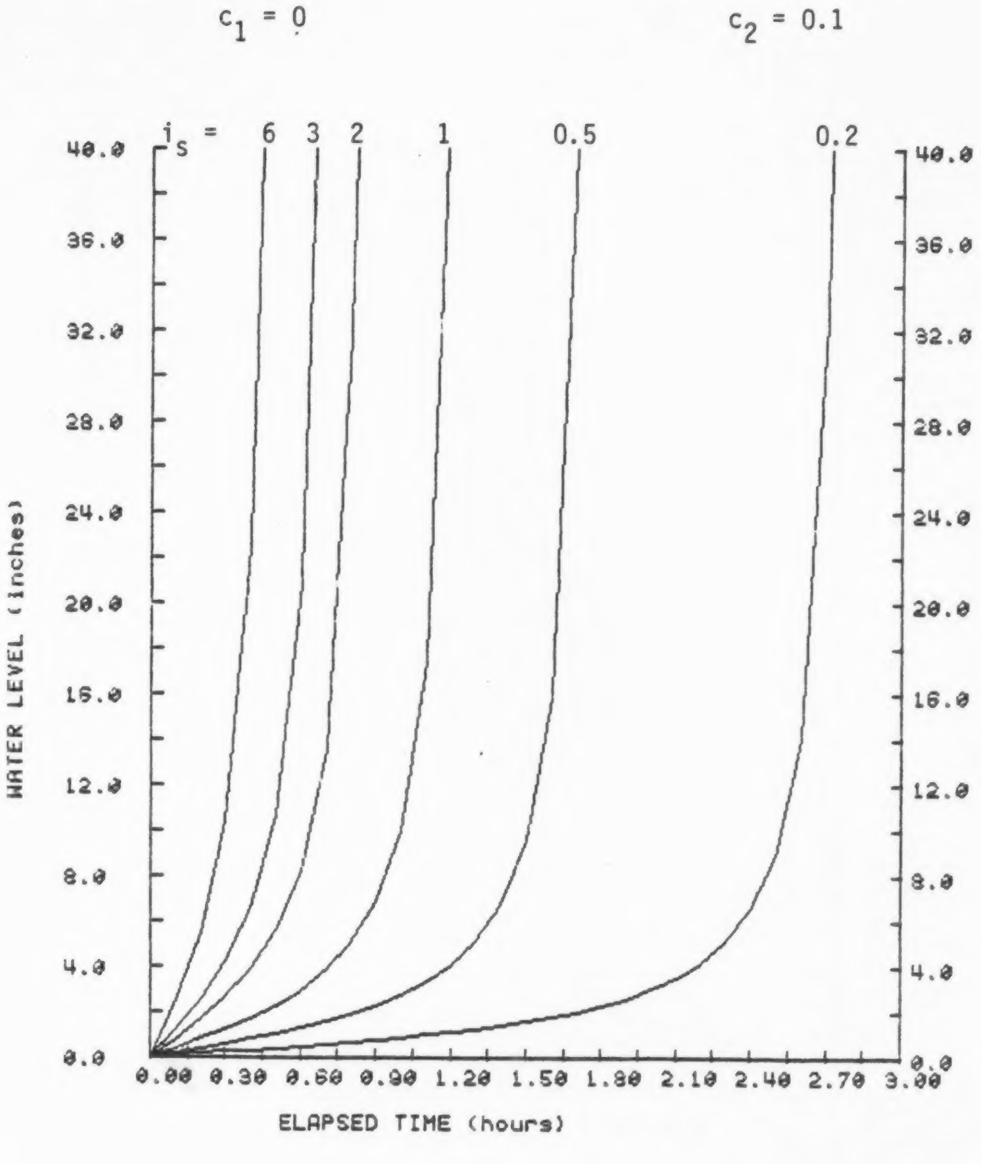


Fig. E13. Water level in the base layer during draining.

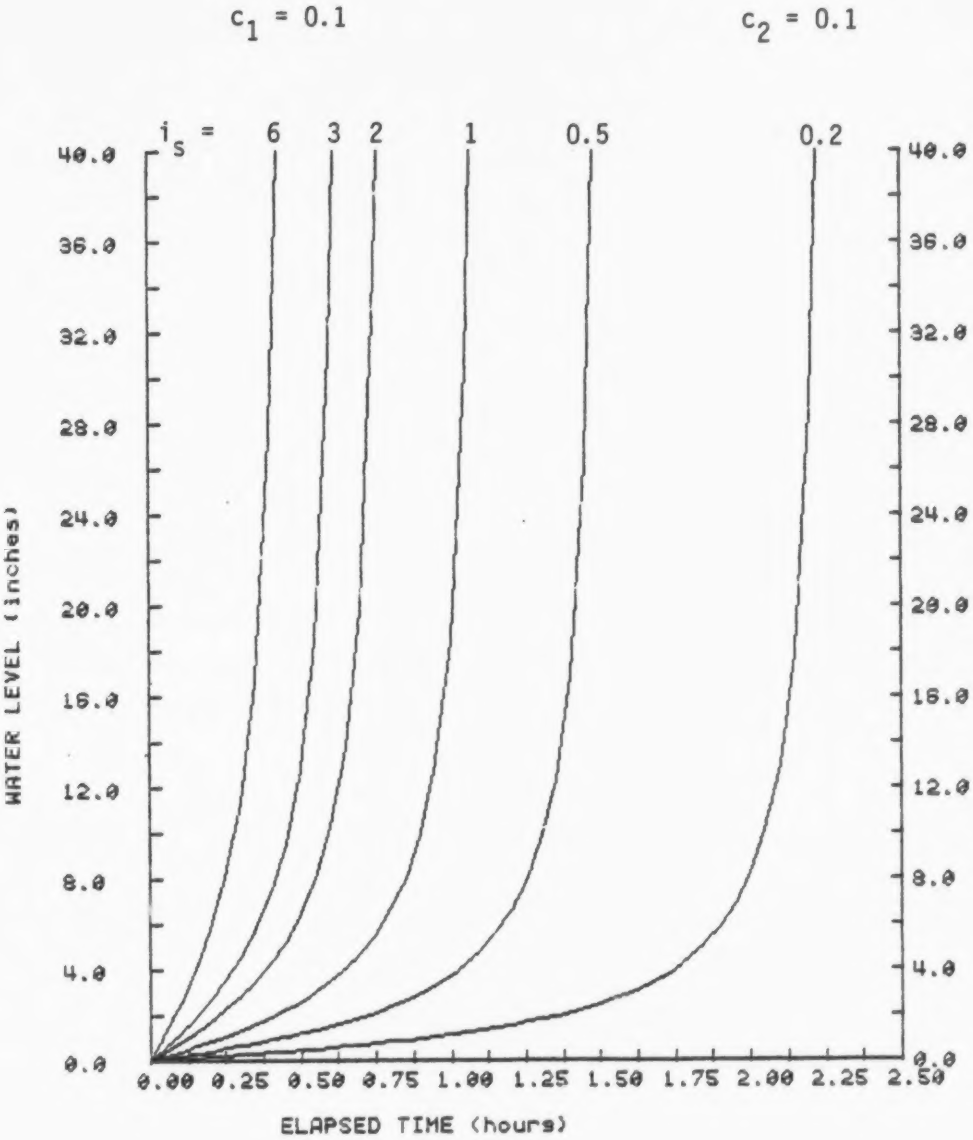


Fig. E14. Water level in the base layer during draining.

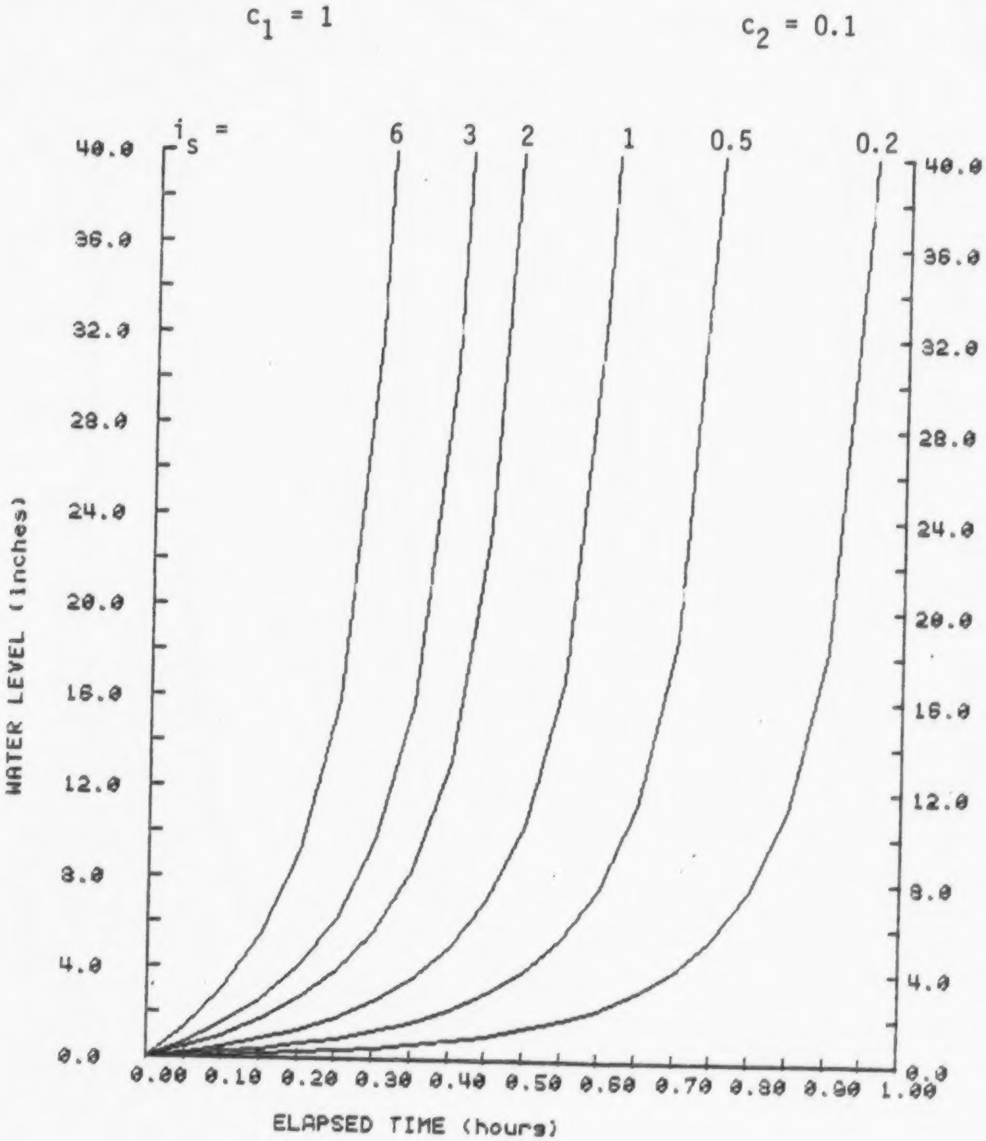


Fig. E15. Water level in the base layer during draining.

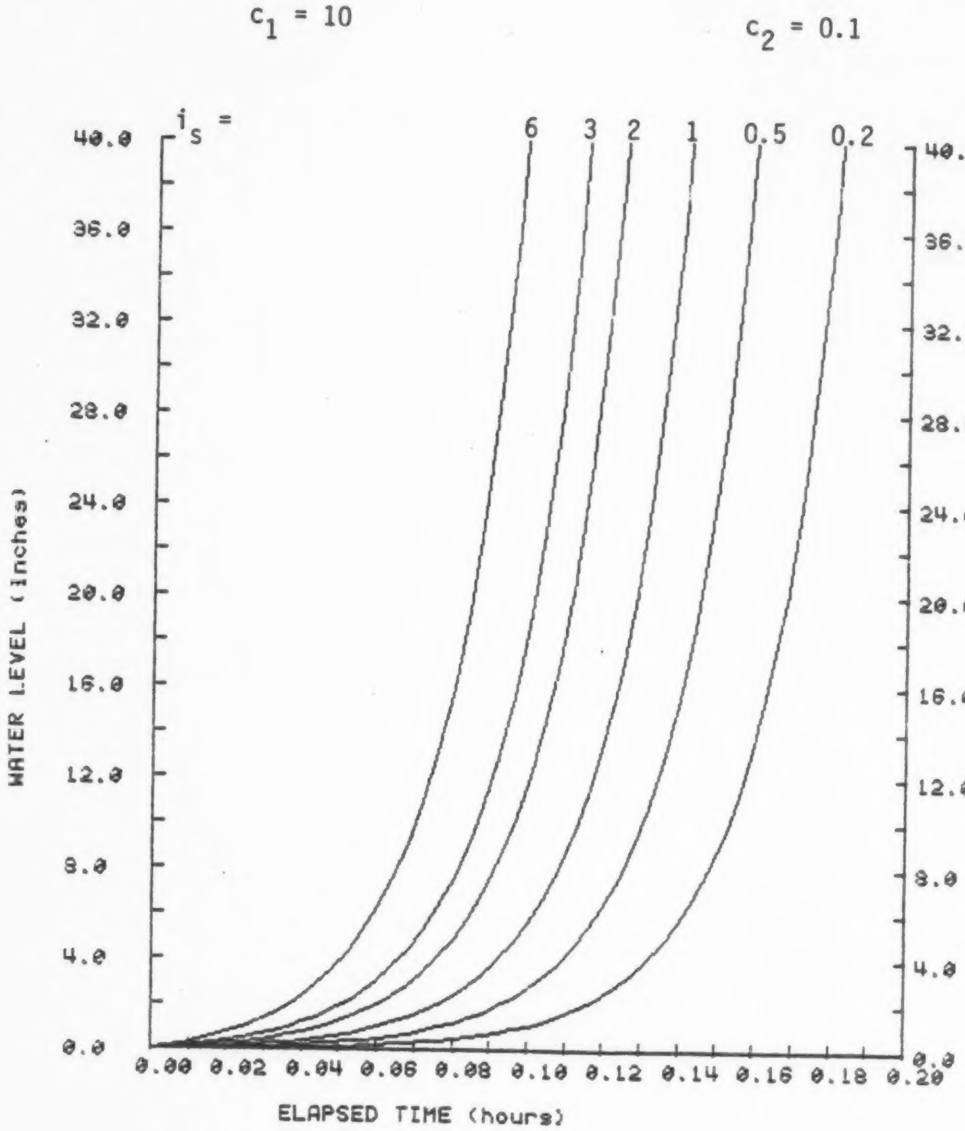


Fig. E16. Water level in the base layer during draining.

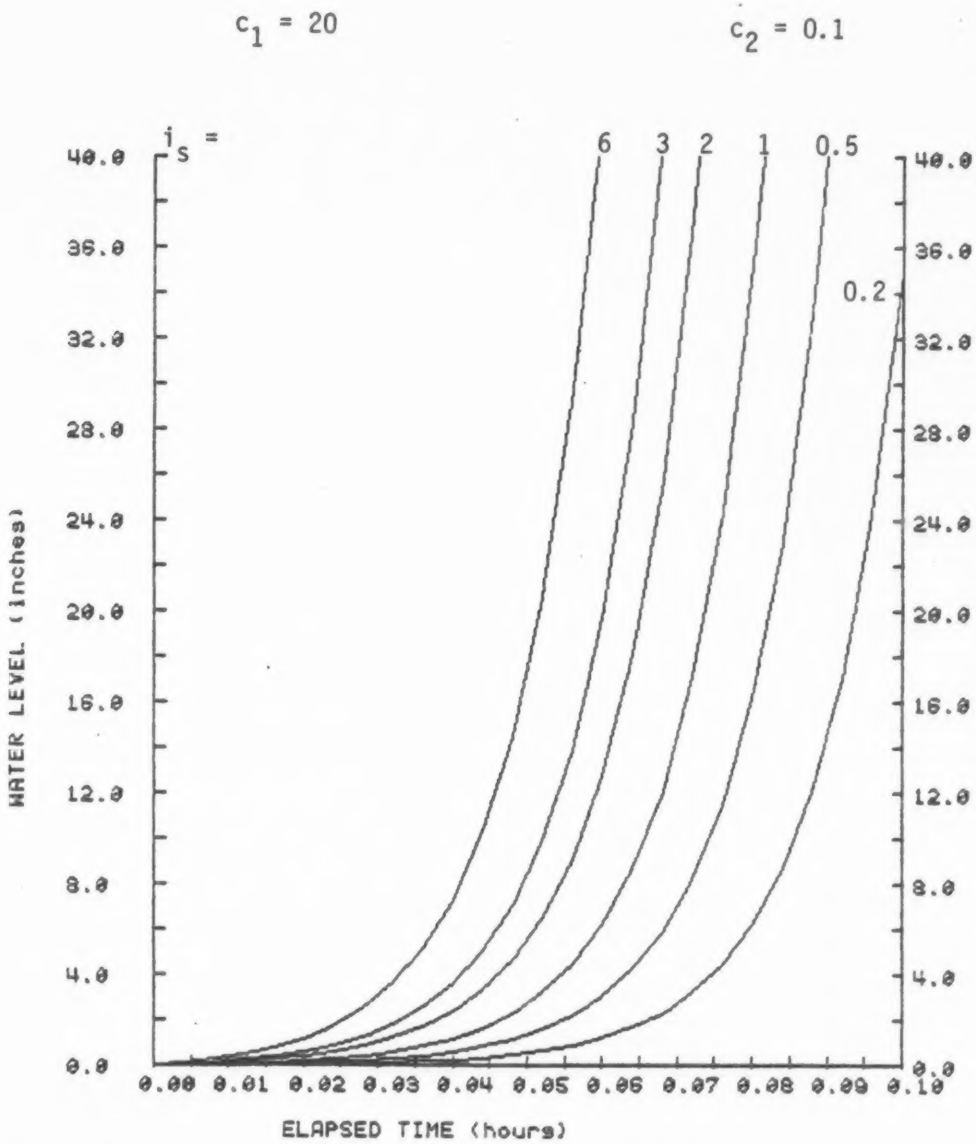


Fig. E17. Water level in the base layer during draining.

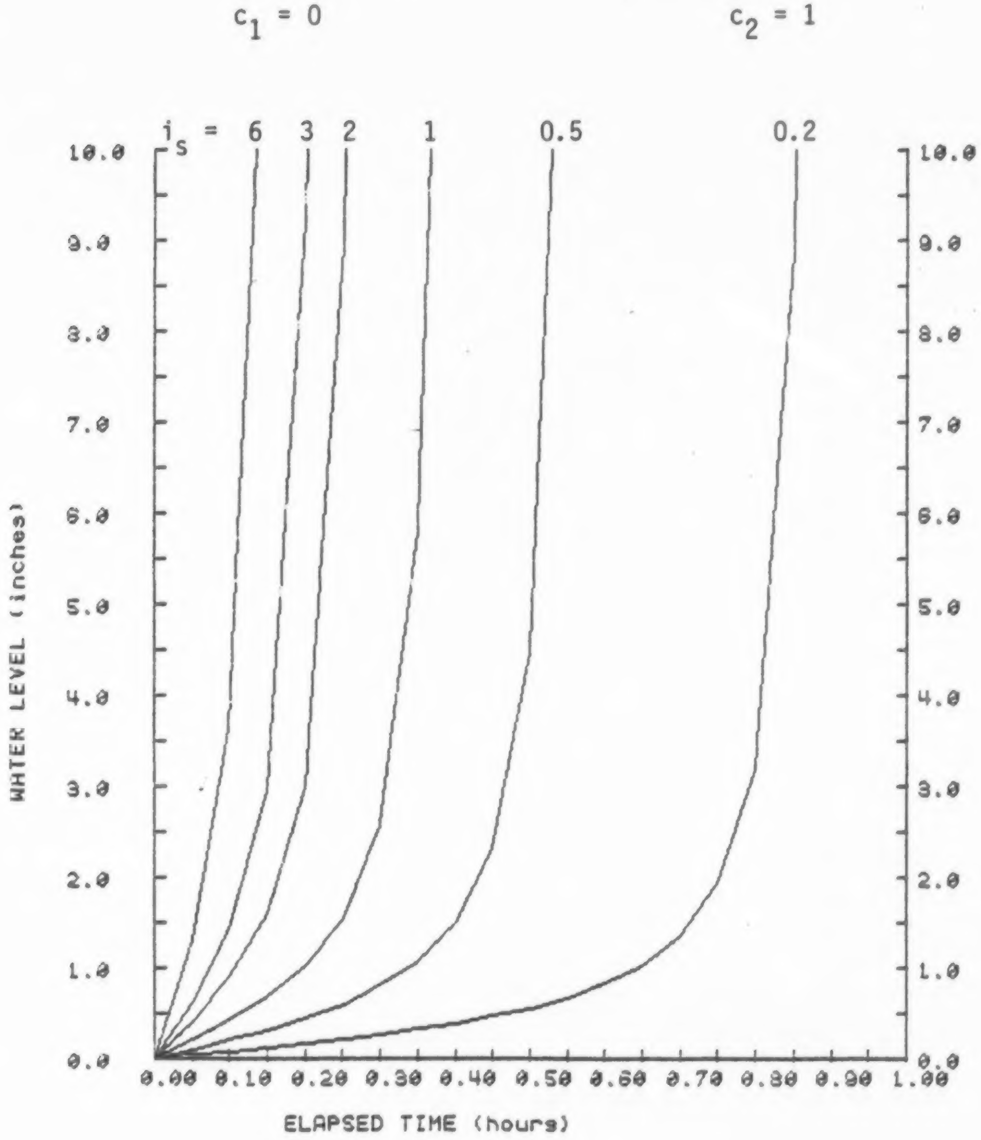


Fig. E18. Water level in the base layer during draining.

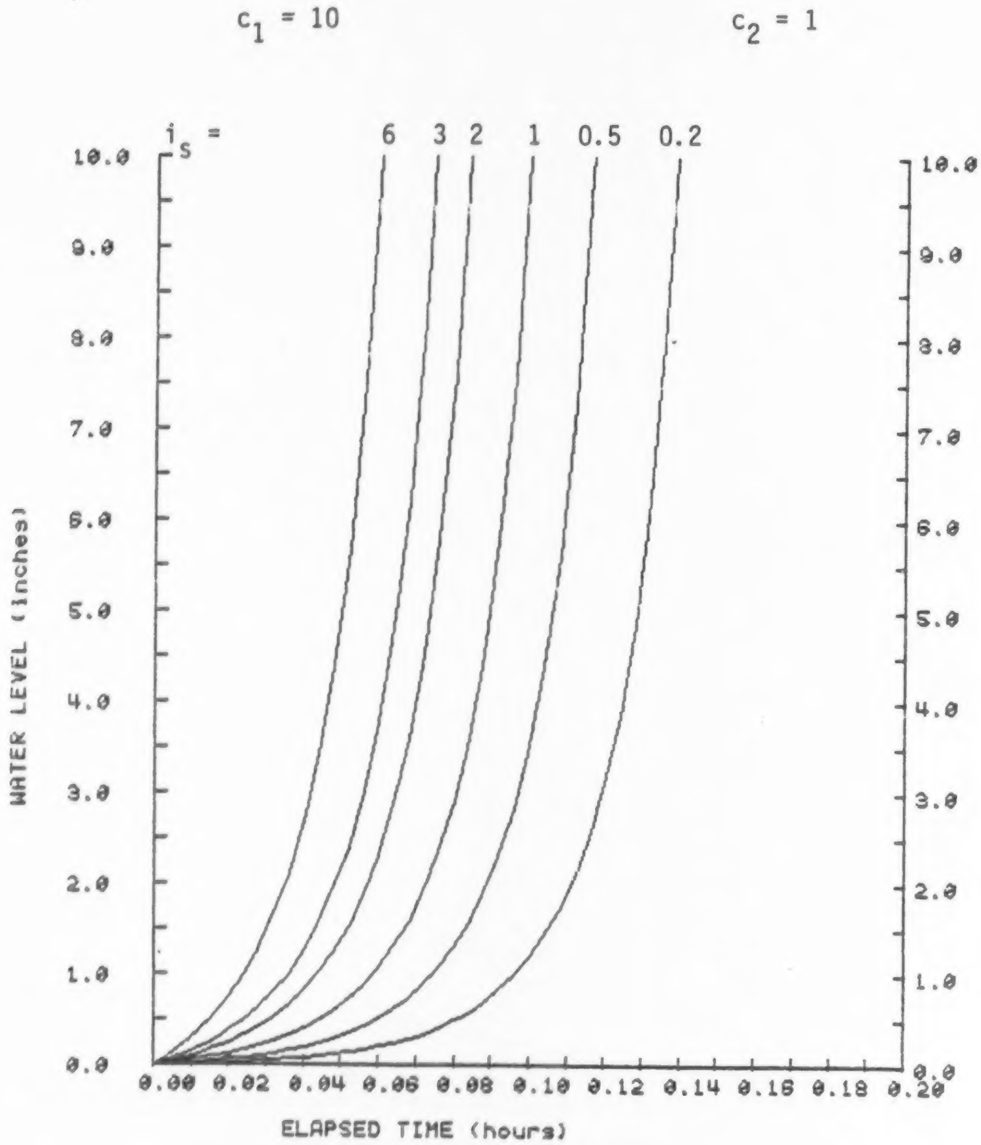


Fig. E19. Water level in the base layer during draining.

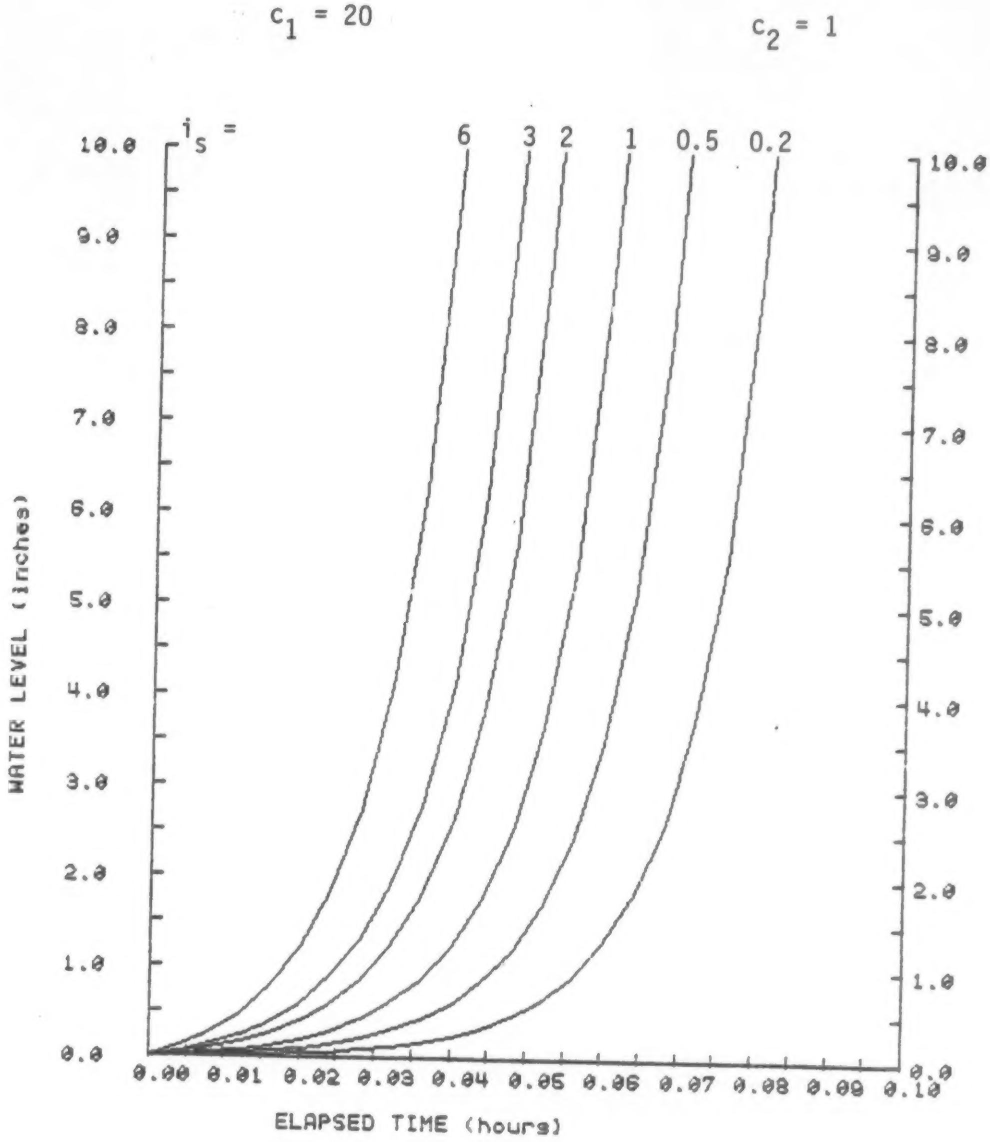


Fig. E20. Water level in the base layer during draining.

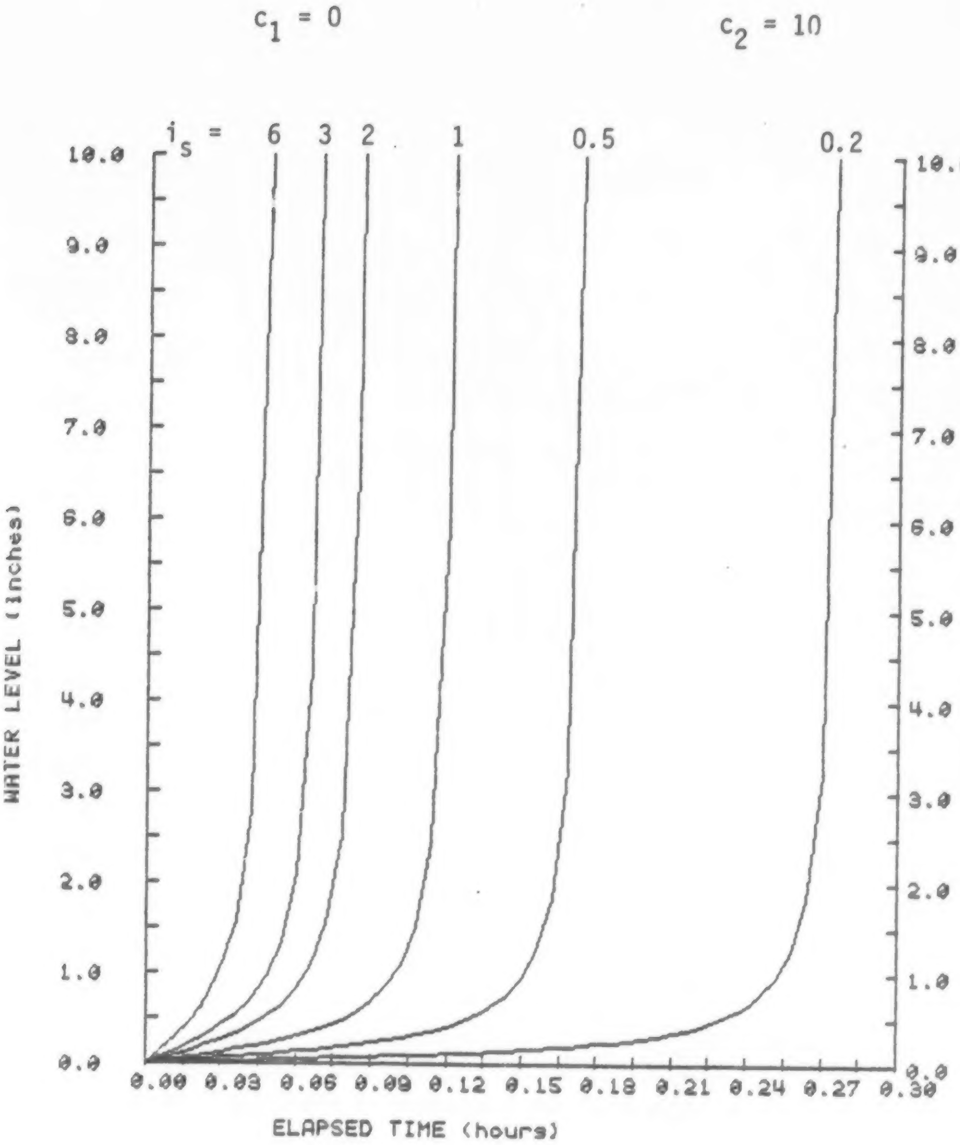


Fig. E21. Water level in the base layer during draining.

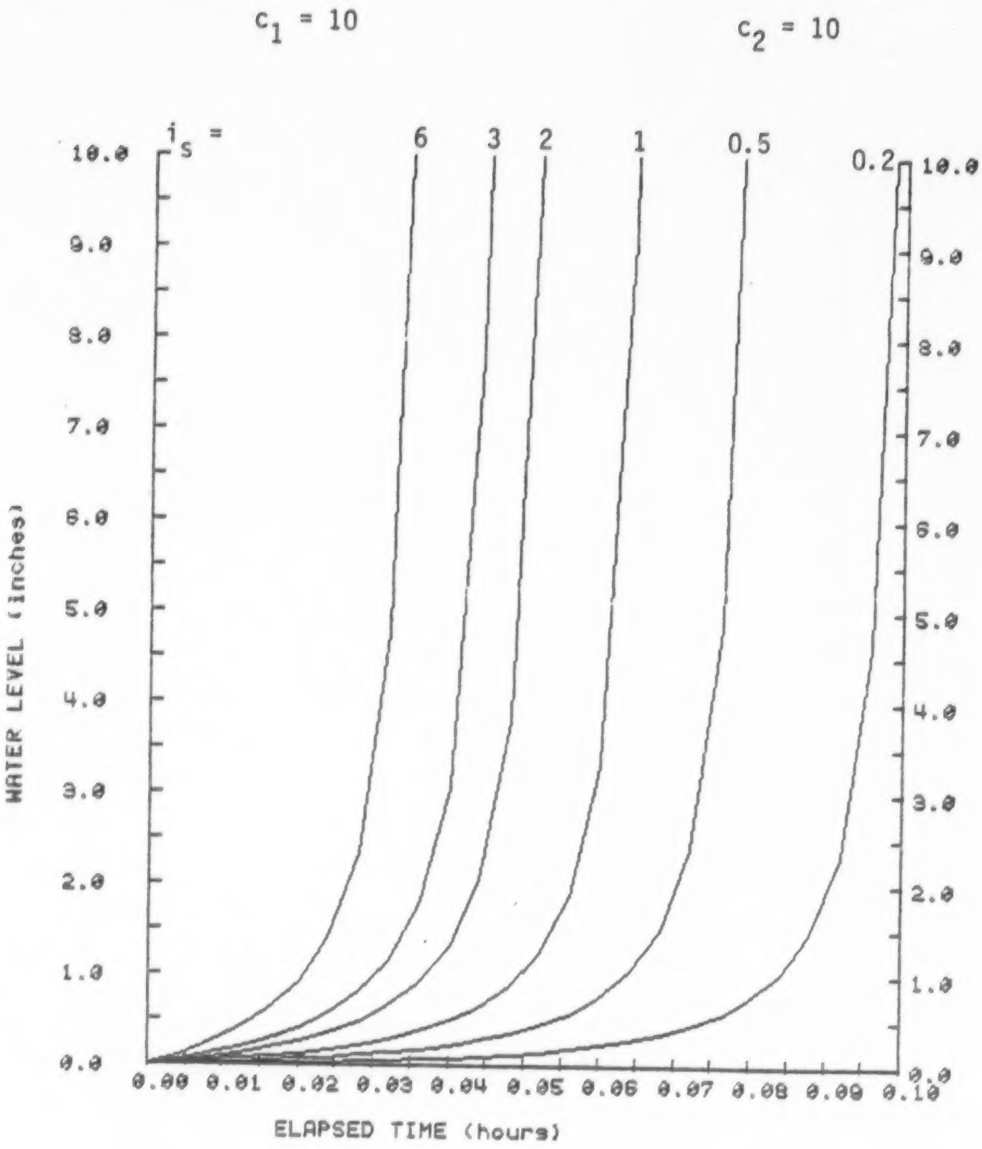


Fig. E22. Water level in the base layer during draining.

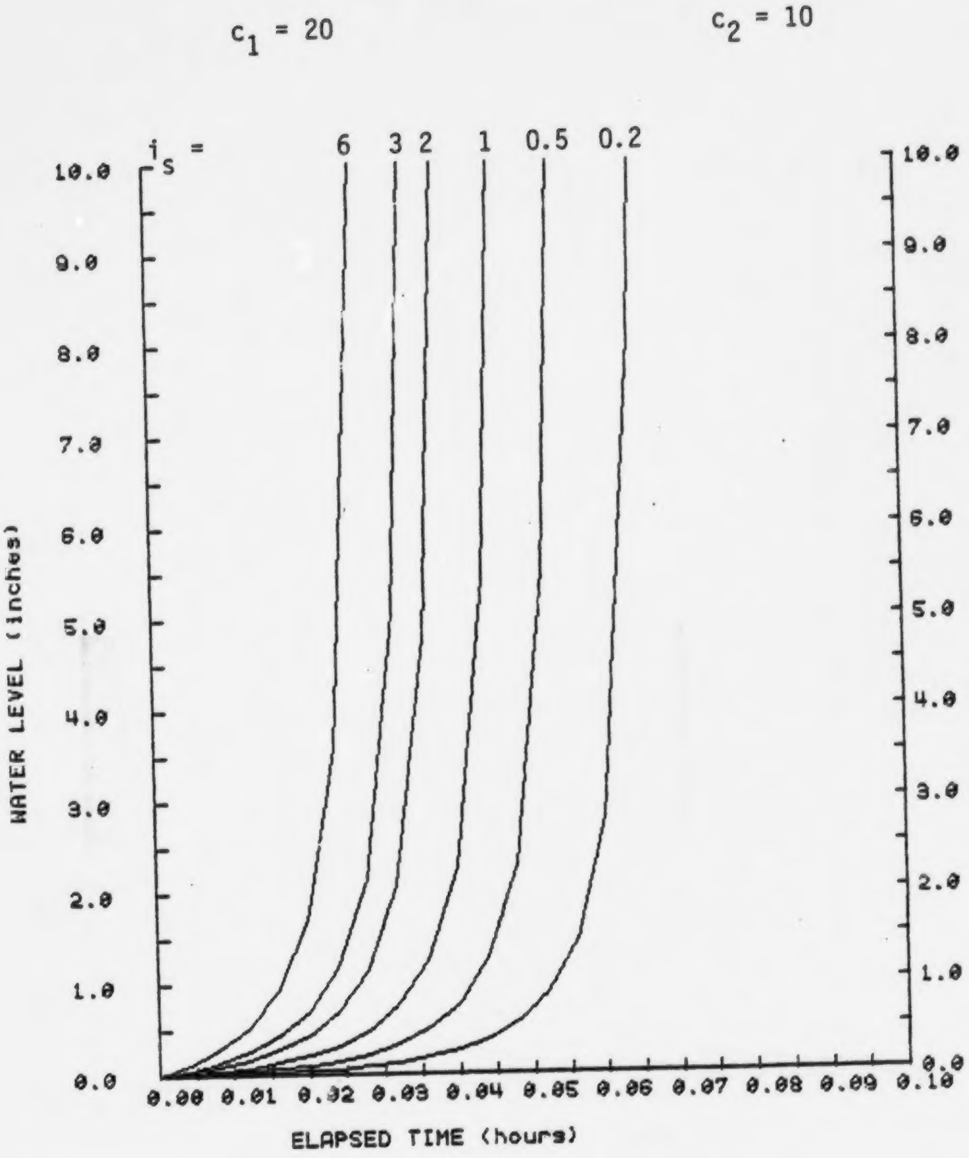


Fig. E23. Water level in the base layer during draining.

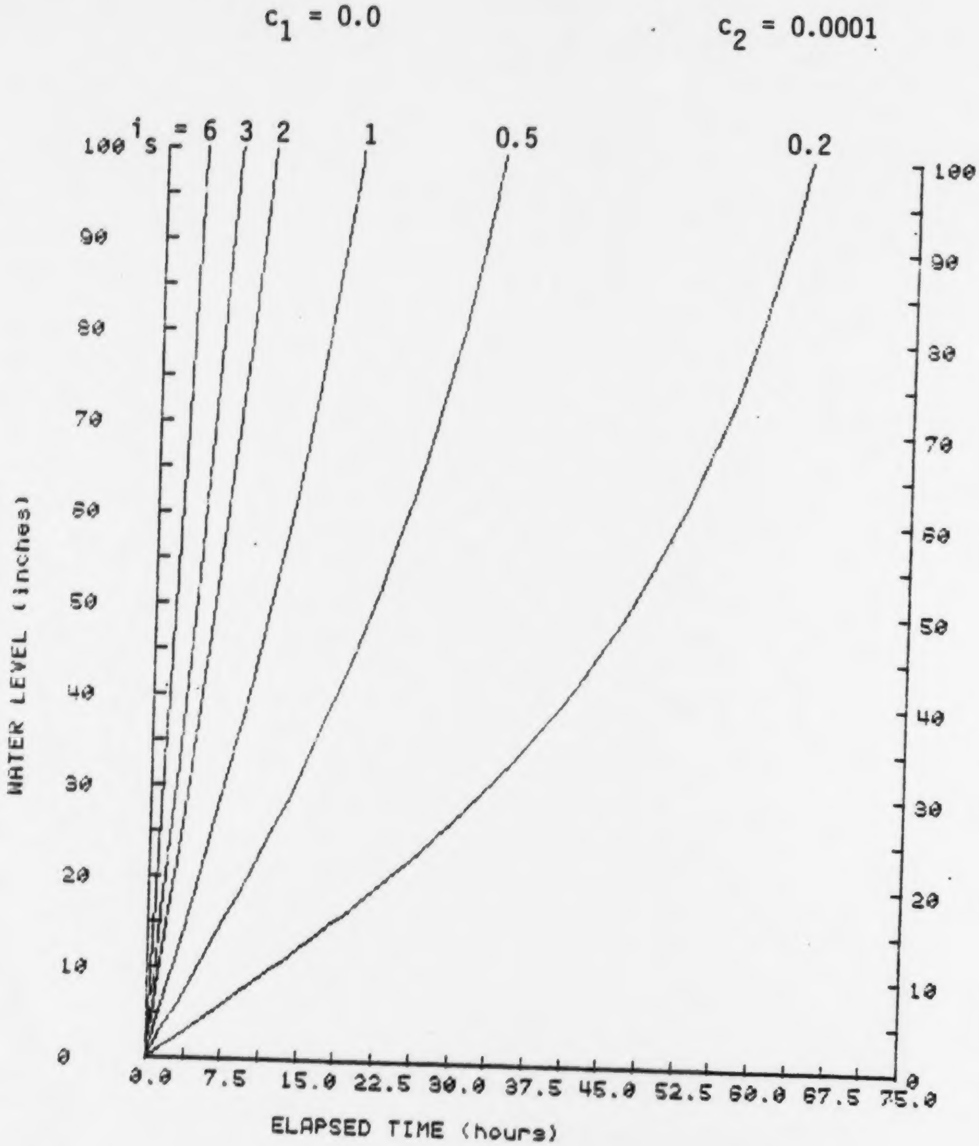


Fig. E24. Water level in the base layer during draining.

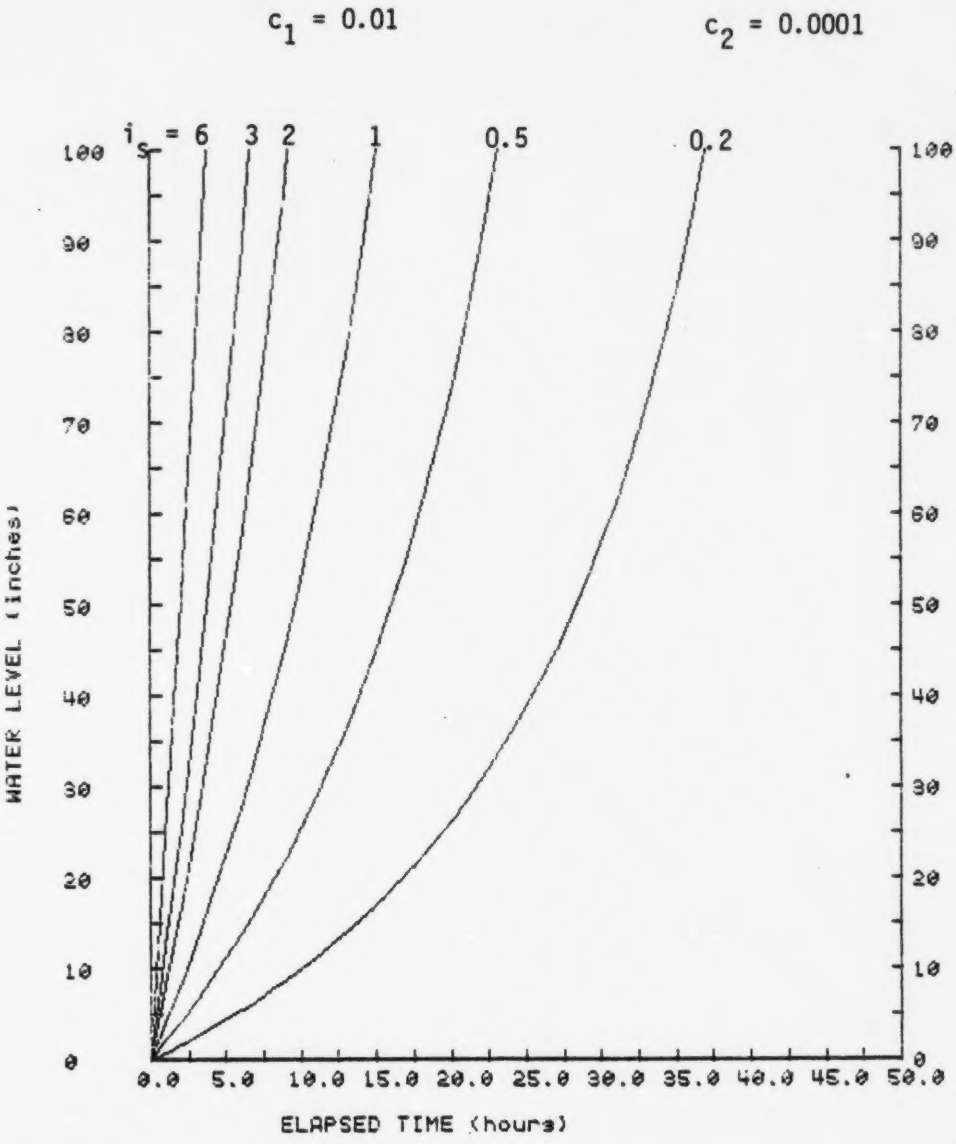


Fig. E25. Water level in the base layer during draining.

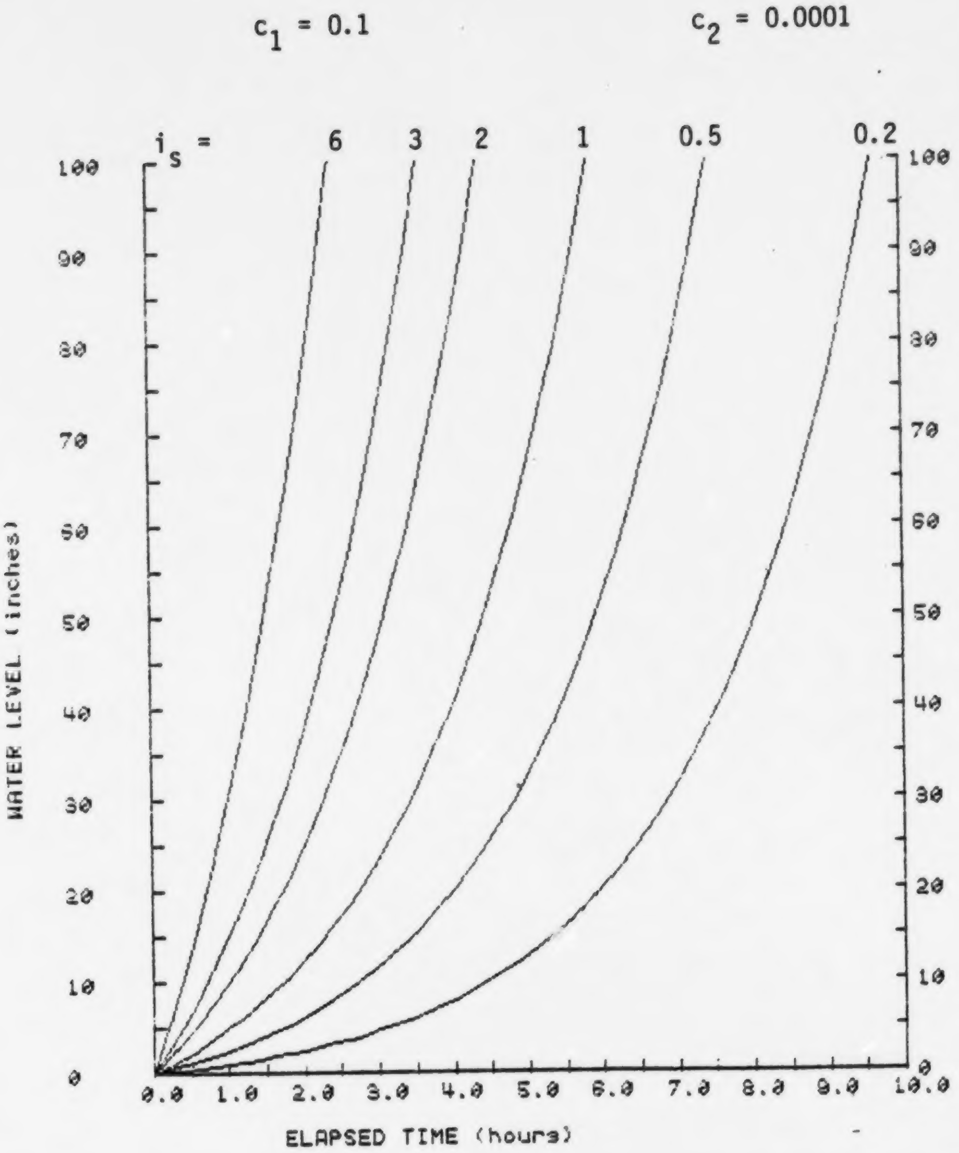


Fig. E26. Water level in the base layer during draining.

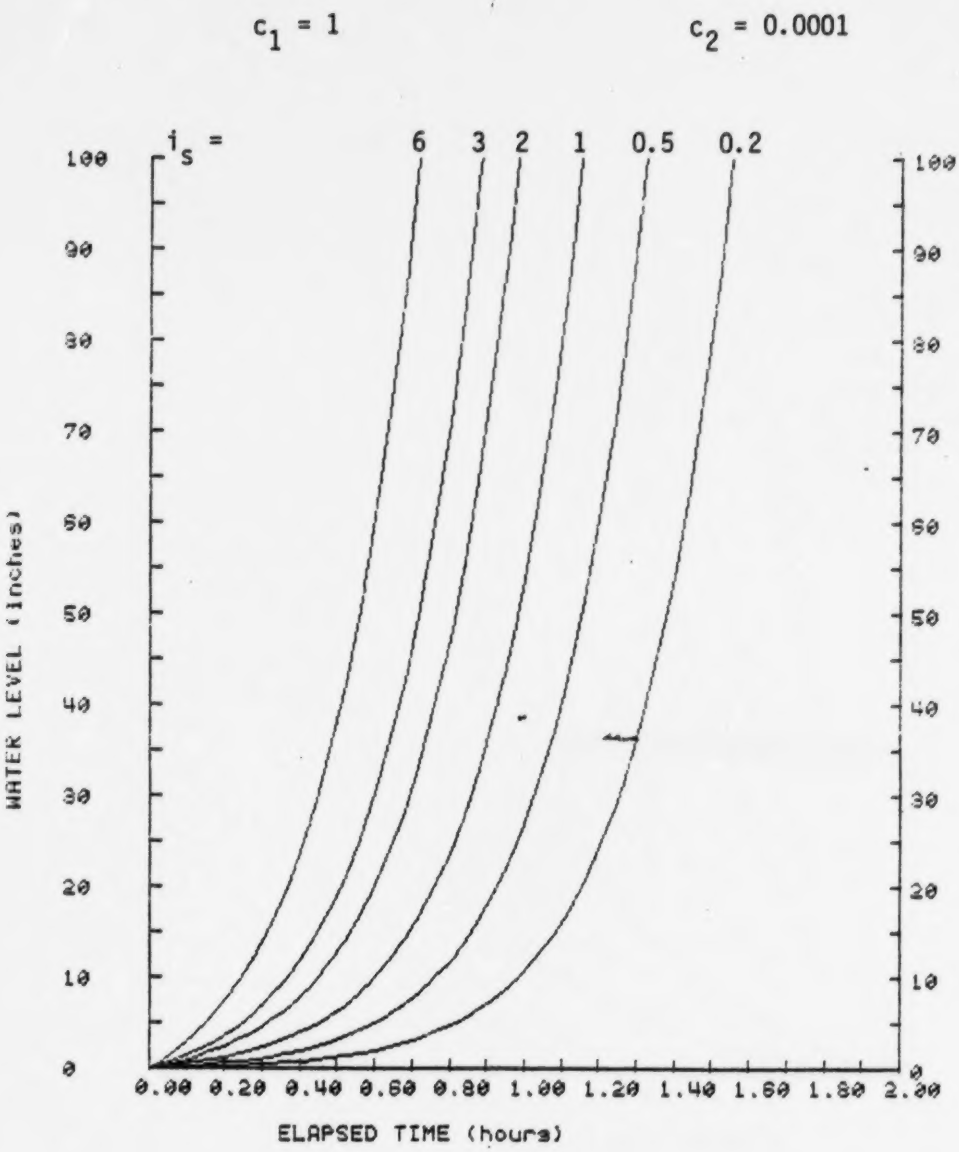


Fig. E27. Water level in the base layer during draining.

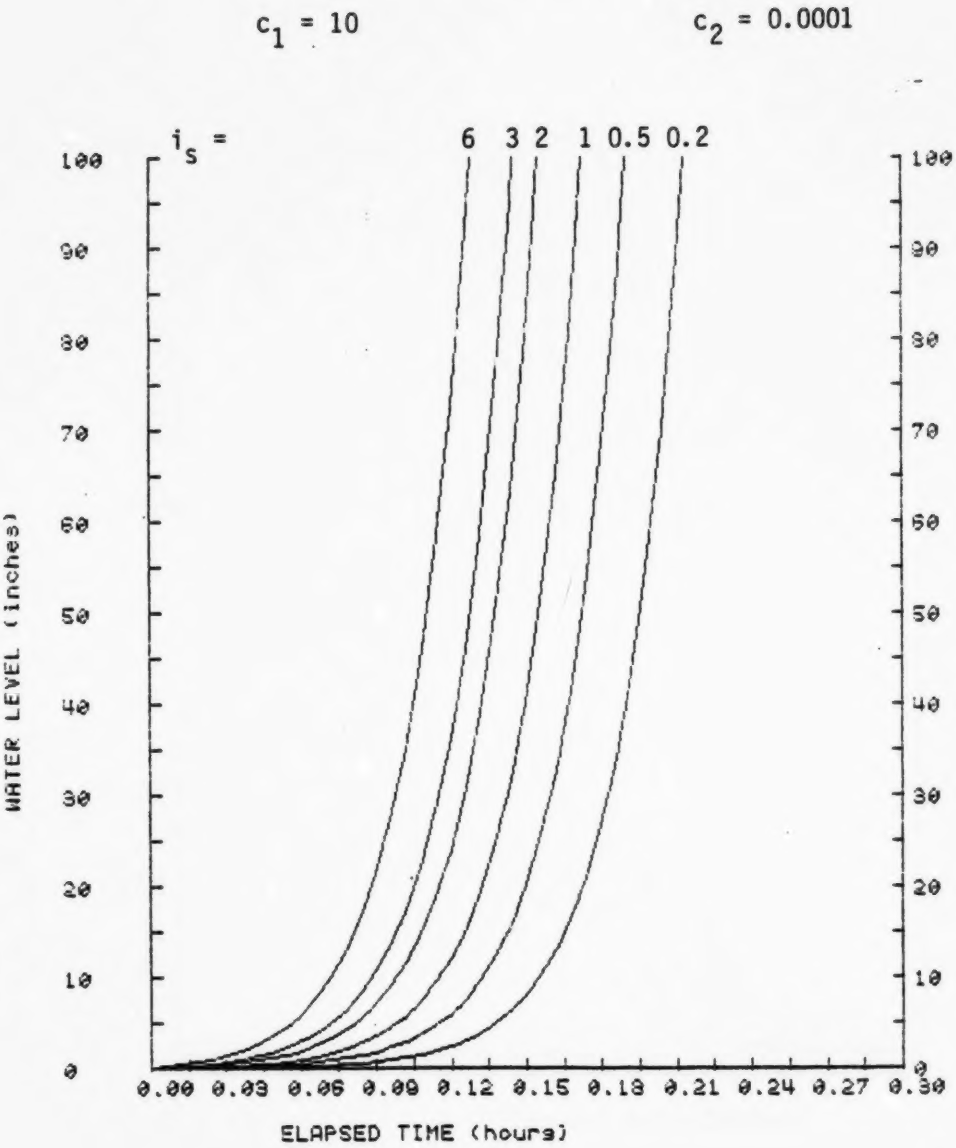


Fig. E28. Water level in the base layer during draining.

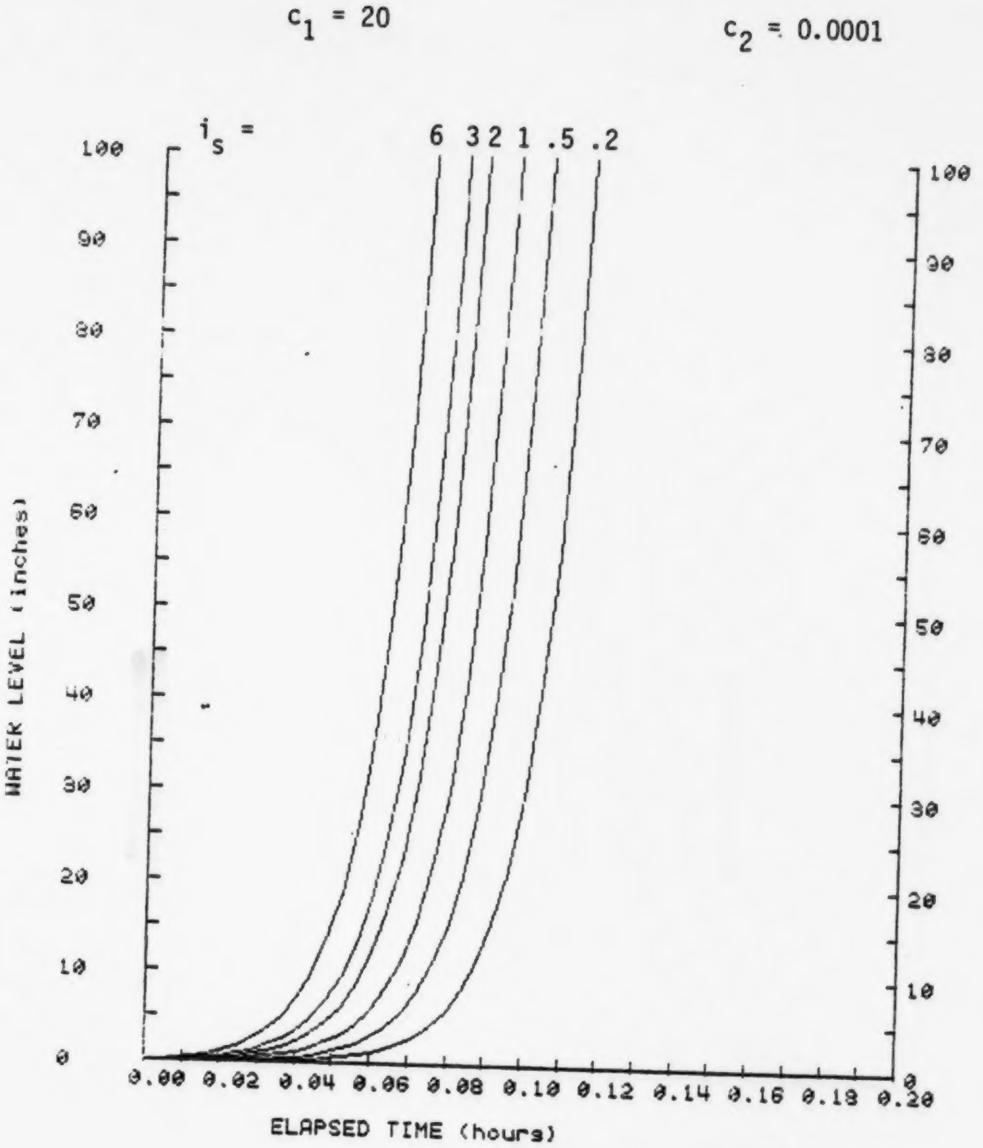


Fig. E29. Water level in the base layer during draining.

APPENDIX F. WATER LEVEL ON THE PAVEMENT SURFACE AFTER THE BASE LAYER HAS BEEN FILLED

$c_4 = 0.01$

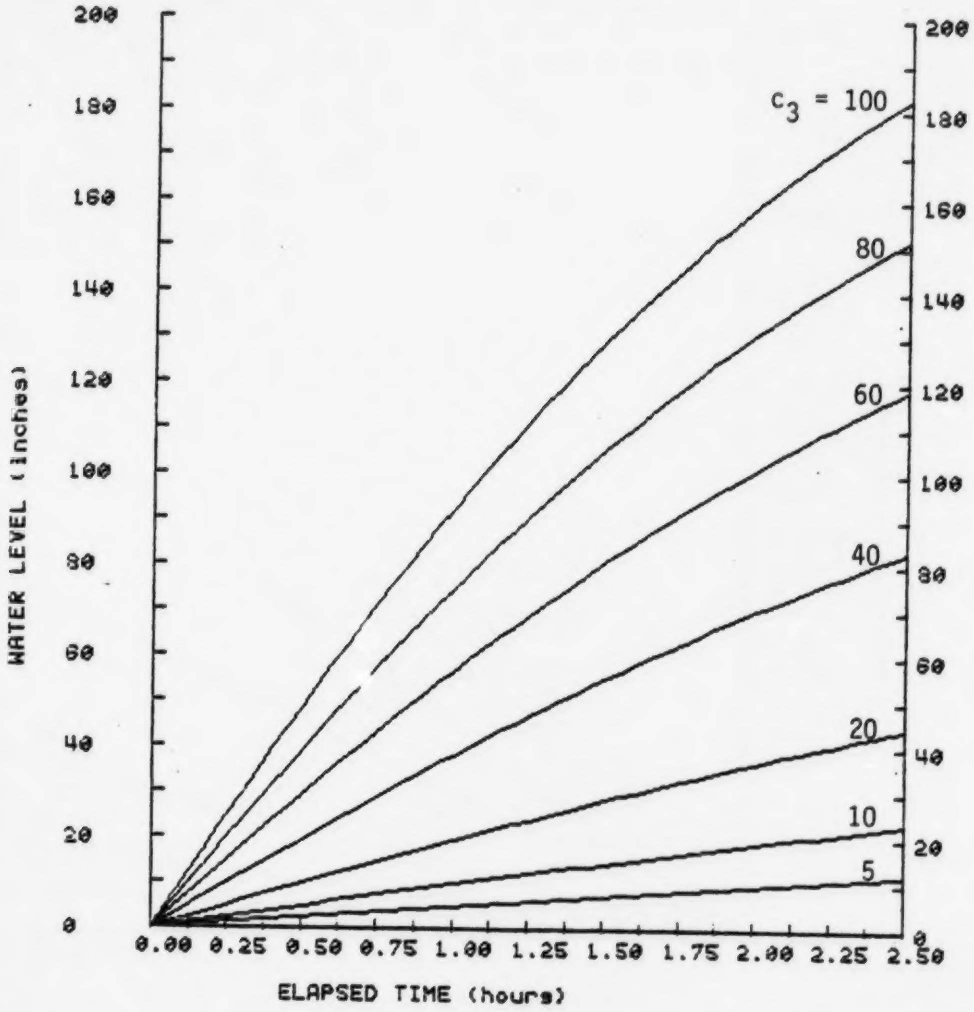


Fig. F1. Water level on the pavement surface after the base layer has been filled.

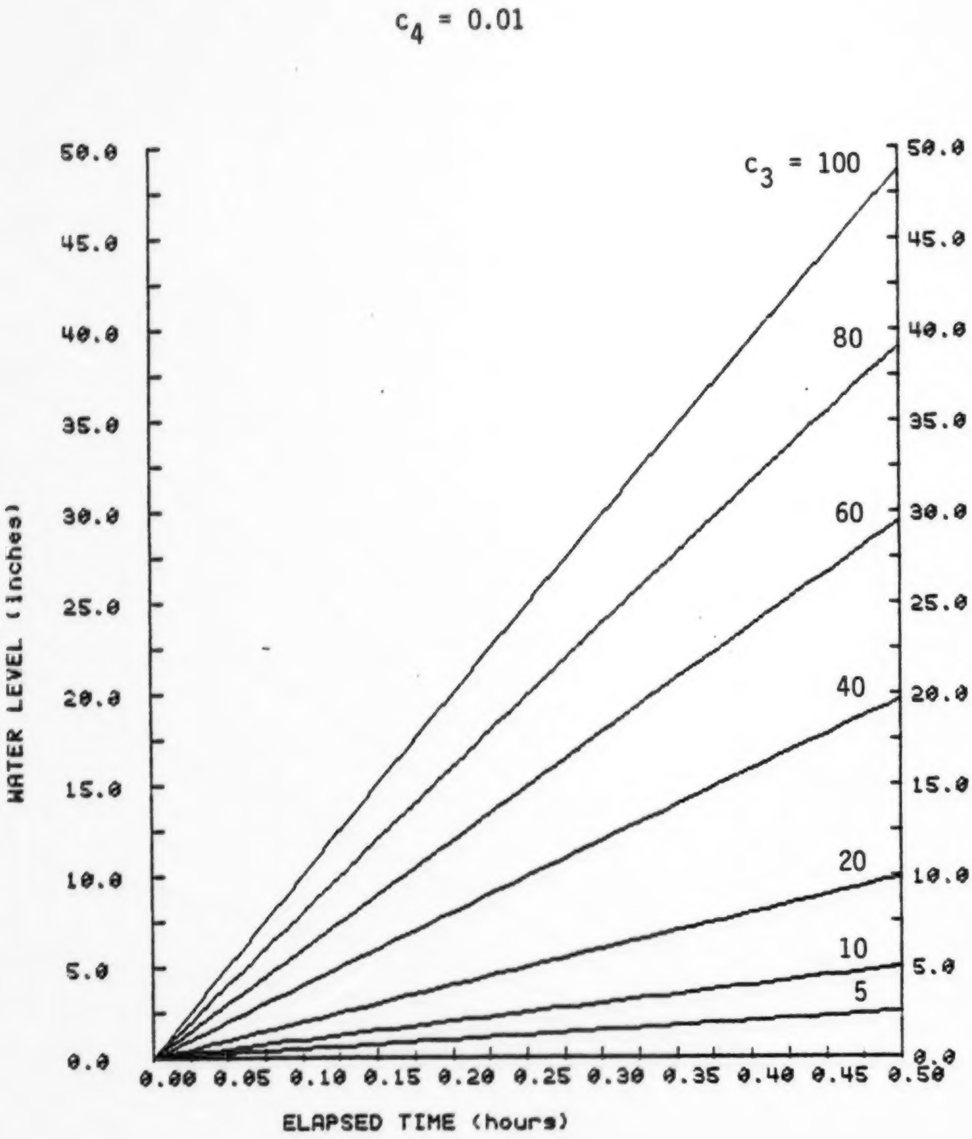


Fig. F2. Water level on the pavement surface after the base layer has been filled.

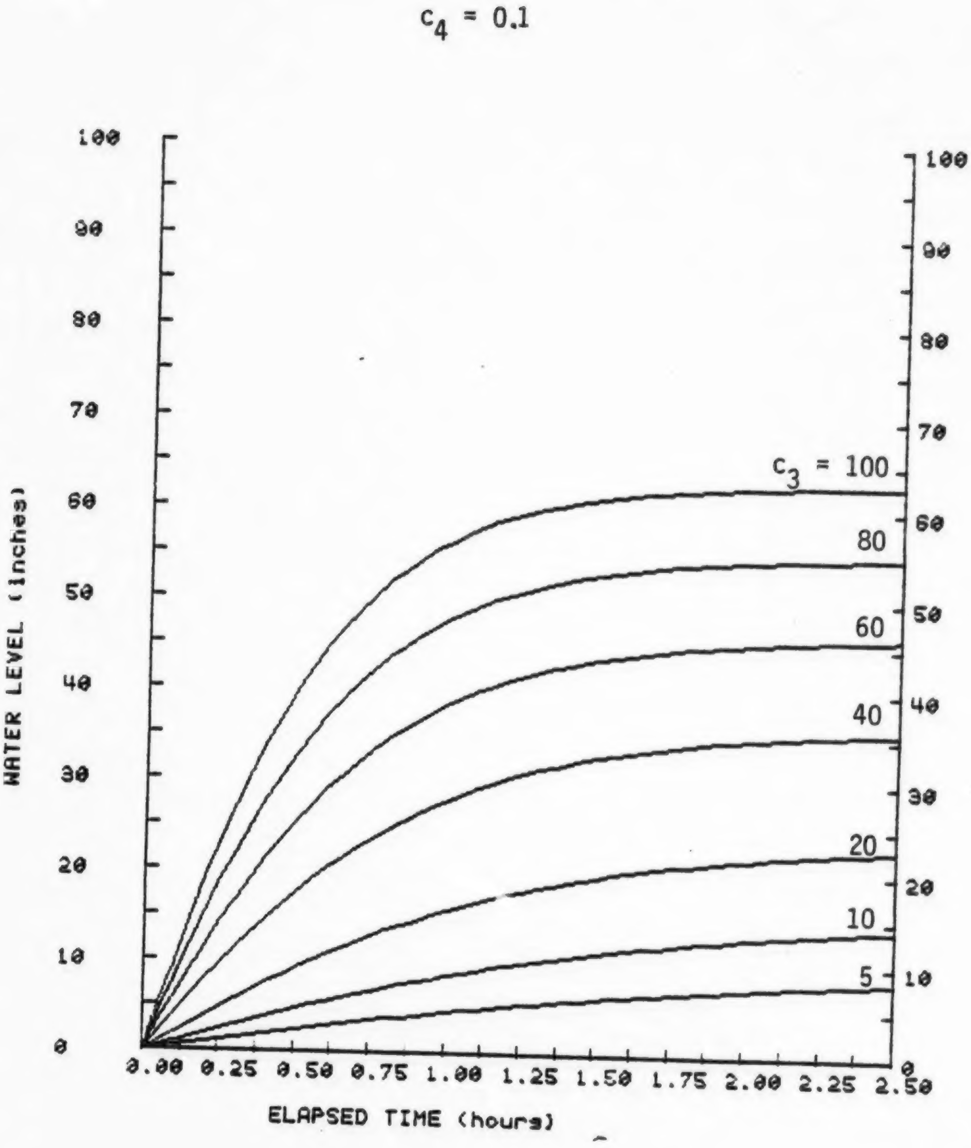


Fig. F3. Water level on the pavement surface after the base layer has been filled.

$c_4 = 0.1$

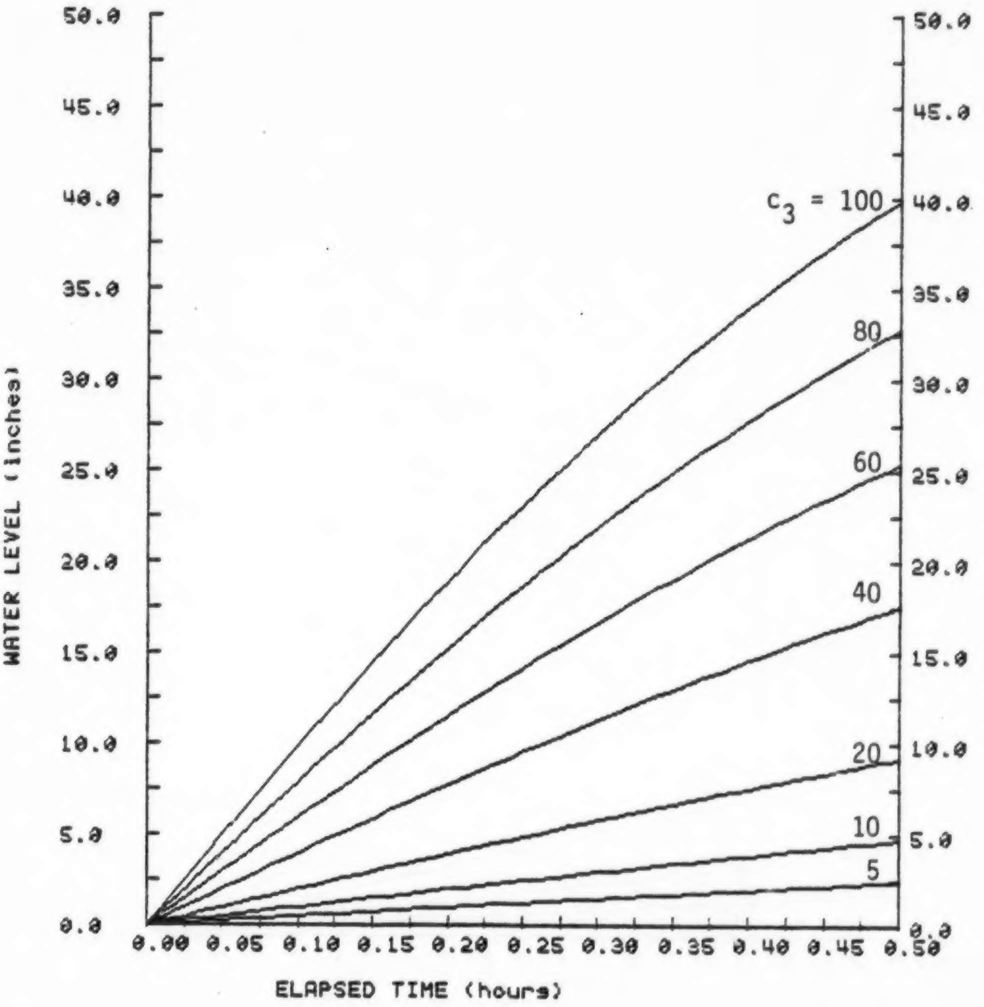


Fig. F4. Water level on the pavement surface after the base layer has been filled.

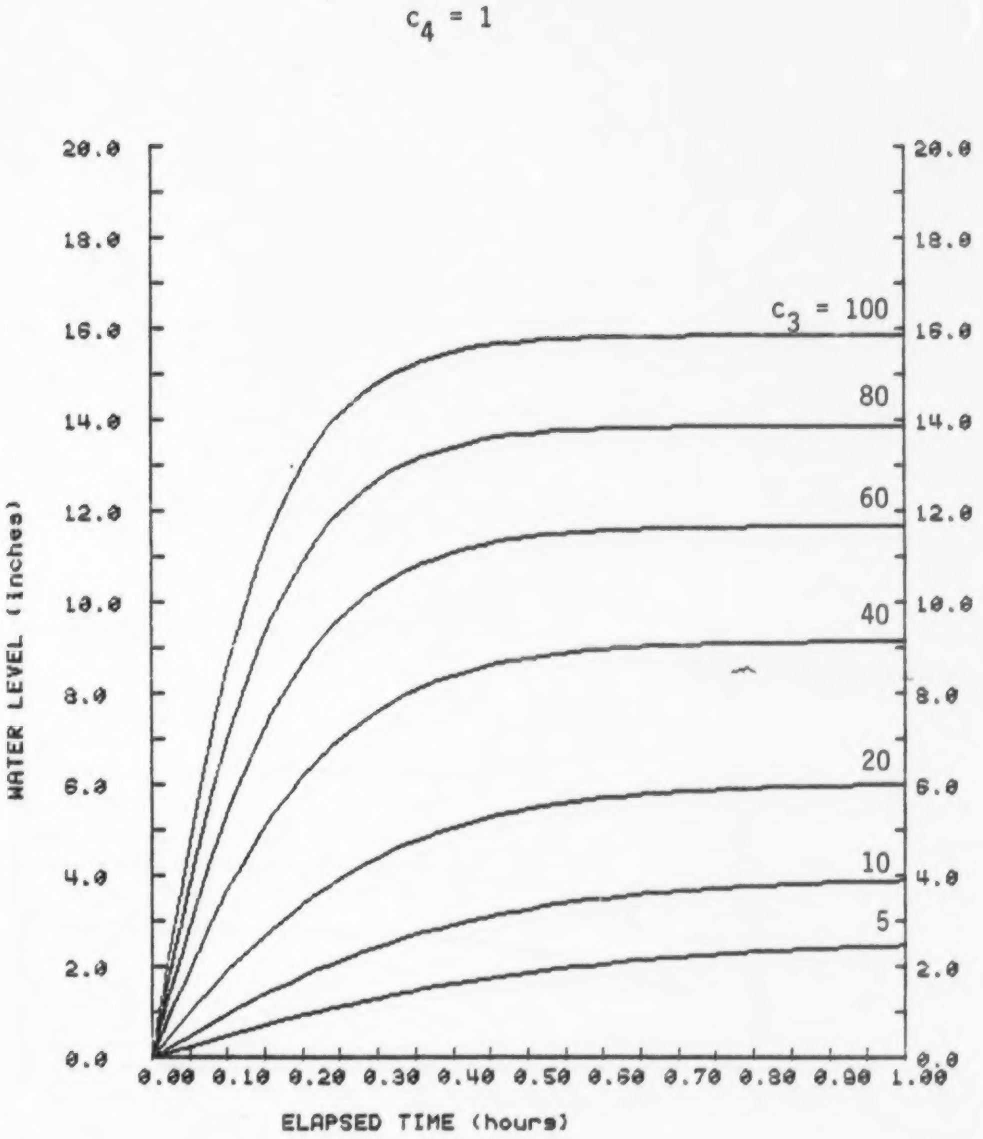


Fig. F5. Water level on the pavement surface after the base layer has been filled.

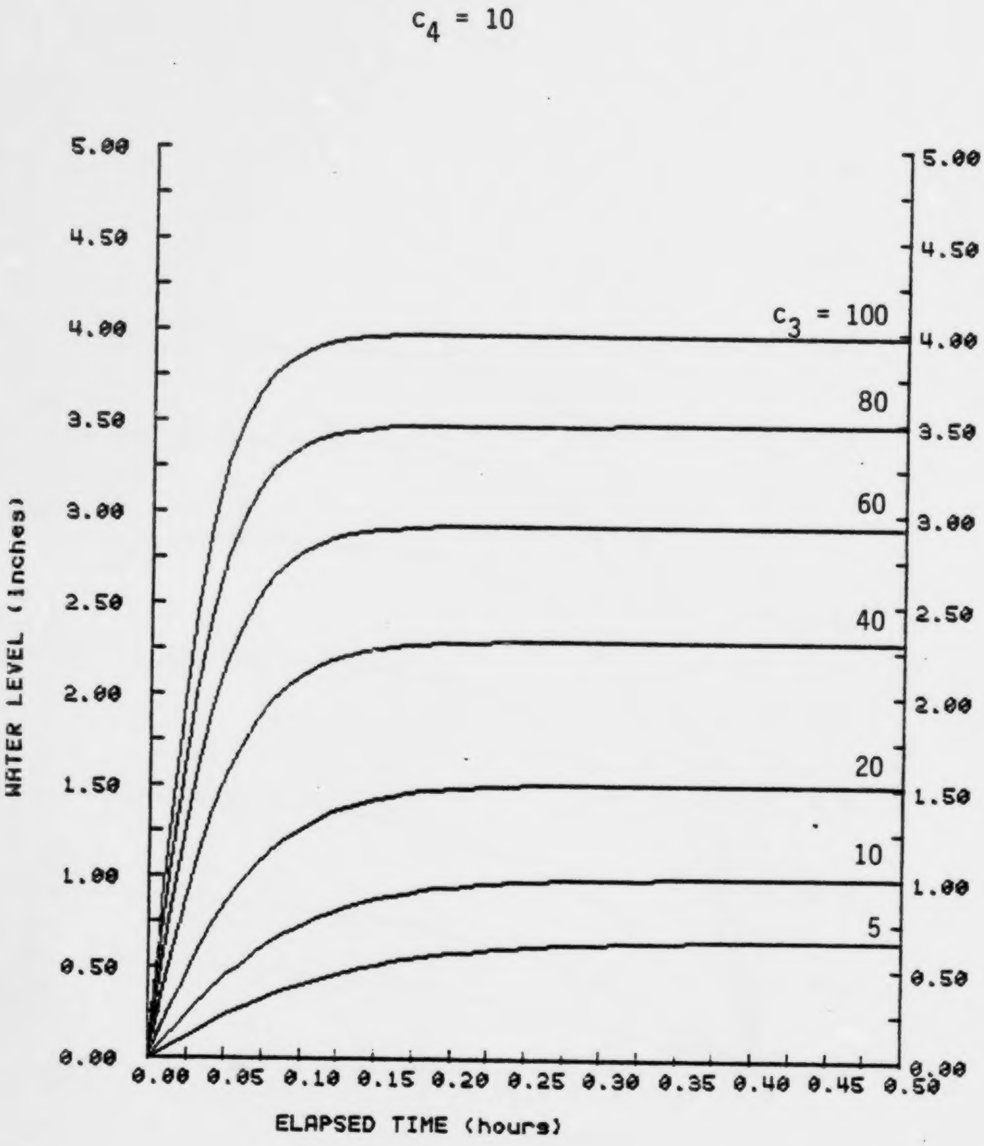
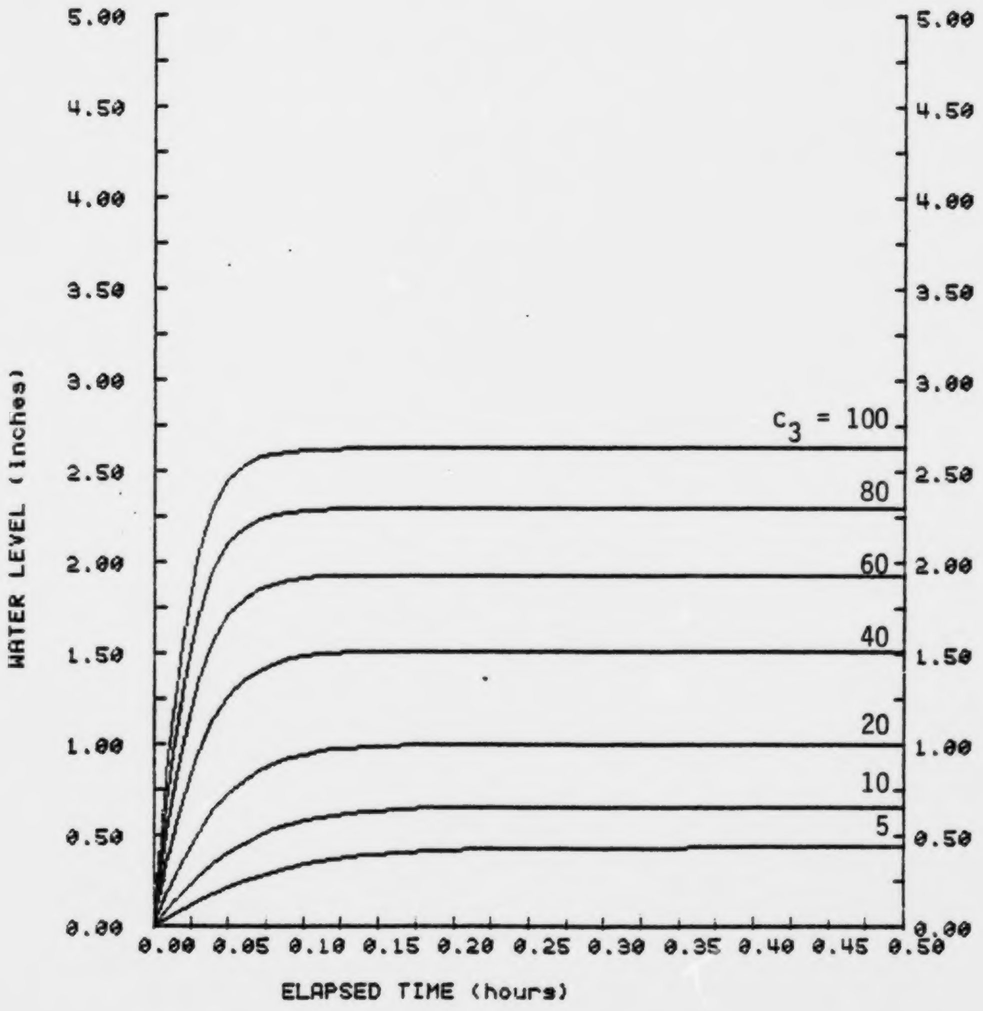


Fig. F6. Water level on the pavement surface after the base layer has been filled.



c_4 = 20

Fig. F7. Water level on the pavement surface after the base layer has been filled.